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JOHNSON'S

MATERIALS OF CONSTRUCTION

REWRITTEN AND REVISED

BY

M. O. WITHEY

Dean, College of Engineering, University of Wisconsin

AND

JAMES ASTON

Consulting Metallurgist with the A. M. Byers Co. of Pittsburgh

EIGHTH EDITION

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PREFACE TO THE EIGHTH EDITION

Some forty years ago the late Dean J. B. Johnson wrote the following pertinent statement in the preface of the first edition of *The Materials of Construction:*

"The rational designing of any kind of construction involves a knowledge of:

"The external forces to be resisted, transformed, or transmitted;

"The internal stresses resulting therefrom;

"The mechanical properties of the materials to be employed to accomplish the objects sought.

'Of these three coordinate departments of knowledge the first two are founded on the sciences of mathematics and applied mechanics. The last one, however, does not rest on any deductive science, as this information can only be gained by patient, expensive, and competent research. For this reason the third essential named above has not kept pace with the other two kinds of engineering science; but, on the other hand, it furnishes very much greater rewards to the skilled investigator.

'During the past twenty-five years the number of such investigators has increased from a scattering few to hundreds and even thousands, and they are now found in all enlightened nations. The results of their original studies and experiments are pouring in upon us from all countries, in many languages; and no practising engineer can hope to even scan, much less to appropriate and assimilate, more than a very small part of the vast wealth of experimental knowledge."

The belief that it was essential that students and engineers should have a broad knowledge of this subject led that author to compile his well-known treatise. His good judgment and foresight in so doing were confirmed by extended use of the book both as a text and as a reference book for nearly a score of years with little revision. In 1918 under the editorial super-on of Dean F. E. Turneaure, now Emeritus, the present authors rewrote book, producing the fifth edition. In it the division into parts was arded and the related portions of the subject were more closely coordi-ted than in previous editions. That edition covered subject matter ilar to the first twenty-nine chapters of this volume. In the sixth tion of 1924, Chapter XXX on paints and varnishes by O. A. Hougen d Chapter XXXI on the constitution of some of the more important non-ferrous alloys by R. A. Ragatz were added, and numerous revi of data and substitutions in descriptions of apparatus were made. 1930 the seventh edition appeared, embodying material changes in chapters dealing with timber, cement, and concrete, and many c minor revisions.

Believing that there is a distinct advantage in presenting to the stu of this subject a book which will serve both as a text and as a refer book, the authors of the eighth edition have maintained the broad sc of the former treatise. They have aimed to provide the essential in mation concerning the sources, manufacture, or fabrication of the princ materials; to give carefully selected data covering the more import mechanical and physical properties and the influences of various fac upon these properties; to show the causes of defects and variations . how they may be discovered; to furnish an acquaintance with the techn of testing materials; and to present to the student some of the m general uses of the different materials.

Great care has been taken to illustrate adequately the revised wo with material from the best sources. In the eighth edition seventy- new and thirteen revised illustrations are presented. The large use diagrams and charts in presenting facts and laws, and the omission tables wherever possible, have featured the present volume as they the previous editions. Dean Johnson well said:

"A law of relationship cannot be perceived from data arranged a tabular form. When plotted to significant arguments the law not o becomes evident at a glance, but when once impressed on the mind thro the sense of sight it cannot well be forgotten. To obtain this lasting be fit, however, the diagram must be intelligently read and understood. T reader is urged, therefore, to give great care to the study of all the diagra which accompany the text on any subject, for, as a rule, the facts, laws, a conclusions to be drawn from them are not fully expressed in the te The diagrams must be considered as a part of the text, and they should read with even greater care than is bestowed on the word-embodied ide

In the eighth edition extensive revisions have been made. Statisti data have been brought up to date. Chapters I to III have been revi to include new definitions, column formulae, formulae for strength deflection of flat plates, information on elastic break-down, new test machines and apparatus, and improved methods of testing. In chapters on timber, information on termites, plywood, and joint fasteni and new grading rules and stress grades for structural timbers are present New data on properties and new methods of testing stone appear Chapter VII. Recently developed methods for testing and new data strength and durability of clay products, together with an article reinforced brick masonry, will be found in Chapter VIII. Extensi

nges in Chapters IX to XII include a résumé of the new types of cement,
gue's method of calculating compound composition, influence of con-
ition on properties, new illustrations of machines and processes of
ufacture, data on properties, and methods of testing. Revised pro-
ires for making and testing mortar and concrete together with new
ormation on the properties of these materials have been placed in
pters XIII and XIV.

Chapters XVI to XXI contributed to the fifth edition by Dr. Aston
l Chapter XXIII have been revised by G. W. Washa, Ph.D. Changes
hese chapters include recent concepts regarding alloy structure and the
stitution of steel, also new illustrations and improved definitions.
pter XXV on cast iron and malleable cast iron has been thoroughly
ised and improved by the insertion of data on new irons and their
erties and uses. Chapter XXVIII on fatigue has been rewritten by
B. Kommers, a new Chapter XXXII, "Metals for Light-weight Con-
uction," has been added, and two new appendices have been substi-
ted for those in the last edition.

Acknowledgment of the many sources of information consulted in the
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MATERIALS OF CONSTRUCTION

CHAPTER I

SYNOPSIS OF THE PRINCIPLES OF MECHANICS OF MATERIALS

GENERAL NATURE OF DEFORMATION AND STRESS

1. Definitions.—When a solid body is acted upon by external forces, two results are, in general, produced: (1) the body is deformed to a greater or less extent, and (2) there is developed in the body internal resisting forces which balance the external applied forces. The deformation produced is by some writers called *strain,* but in this work the term *deformation* will be used; that produced in a unit of length is termed unit deformation. The internal forces acting between consecutive particles are called *stresses.* Unit stress is the amount of internal force per unit area. The stresses acting on any imaginary section taken through the body must be in equilibrium with the external forces acting on either side of such section.

If the external forces themselves are not in equilibrium, there is a third result produced, namely, that of acceleration of the body, but in the discussions of this treatise the subject of motion of bodies is not considered; all external forces are assumed to be in equilibrium and the body at rest.

2. Kinds of Stresses.—Depending upon the arrangement and direction of the external forces, the stress produced in a body may be

(1) Tensile stresses;
(2) Compressive stress;
(3) Shearing stress;
(4) Bending stress;
(5) Torsional stress;
(6) Various combinations of the above stresses.

Tensile and compressive stresses are frequently called *direct* stresses. They act perpendicularly to the section in question. In the case of long prismatic bars or members of structures, if the external forces act along the axis of the member, direct stresses of tension or compression are produced, the section taken being assumed as a cross-section transverse to the axis of the member.

Shearing stress is produced by forces tending to slide one particle upon another; it is a stress which acts parallel or tangential to the section in question. Where the resultant of all forces acts in a direction at right angles to a section, the stresses on the section are direct tensile or compressive stresses; where it acts at any other angle, there will exist shearing as well as direct stresses. Generally speaking, when a body is deformed under the action of external forces, both shearing and direct stresses will be produced throughout the body; it is only on particular sections that the stresses will be purely direct or purely shearing stresses. Thus, in the case of a tension bar, the stresses on a transverse section will be tensile only, but on a section taken through the bar at any other angle, shearing stresses will also be present.

Tension, compression, and shear may be considered as the elementary stresses. The other kinds of stresses mentioned above are merely combinations of these elementary stresses resulting from special arrangements of the external forces. Thus, the so-called *bending stresses* are those which are produced by external forces that give rise to bending moments; the resulting stresses are compressive on one side of a neutral plane and tensile on the other side, while shearing stresses exist, in general, throughout the beam. The result of this combination of stresses is a bending of the member as a whole.

Torsional stresses are produced by forces which set up a torsional or twisting moment; this produces a rather complex combination of shearing, compressive, and tensile stresses. The member as a whole receives a twisting or torsional deformation.

Combined stresses are those resulting from a combination of direct and bending stresses which produce a bending of the member and at the same time an elongation or compression, those resulting from a combination of direct stresses, or those resulting from a combination of direct and shearing stresses.

Other common terms, frequently used in defining various conditions under which the external forces are applied, are: impact, repeated stress, and column action.

Impact is a term used to describe the application of external forces with such suddenness as to produce a shock or blow.

Repeated stresses indicates stresses which are applied and removed, in whole or in part, numerous times and at short intervals. In carrying out such tests, stresses are often repeated several millions of times.

Column action signifies a compression applied to a relatively long member so that lateral bending or buckling is likely to occur, thus giving rise to bending as well as compressive stresses.

3. Elastic and Plastic Bodies.—When a body which has been deformed under the action of external forces is released from such action, a greater or less recovery of form takes place. To the extent to which the body recovers its original form, it is said to be *elastic,* and to the extent to which the body fails to recover its original form, it is said to be *plastic.* Most engineering materials are in part elastic and in part plastic, the relation between these properties varying widely in different materials. For relatively small unit stresses and deformations, most materials are nearly or quite perfectly elastic, that is to say, they fully recover their form when the load is removed; but as the deformation increases, a point is reached beyond which the original form is not fully recovered.

Elastic Limit and Ultimate Strength.—The maximum unit stress within which a body is quite perfectly elastic is called the *elastic limit.* Beyond this point, the material will recover only to a certain extent, and will show a certain amount of permanent change of form or set. When the load and deformation are increased still further, rupture generally ensues. The maximum unit stress carried by the material is termed the *ultimate strength.*

The amount of deformation which the material will undergo before rupture, varies widely with different materials. Hard, brittle materials like glass will show very little deformation between their elastic limit and ultimate strength, while materials like soft steel and wrought iron will undergo a very large deformation between these limits. Under compressive stresses materials like soft steel and wrought iron can hardly be said to have any definite ultimate strength, as their resistance to load increases continuously with their deformation.

4. Modulus of Elasticity.—Within the limits of elasticity of solid bodies, the deformation is proportional to the stress, and the ratio of unit stress to unit deformation is a very important function in the study of materials. In general, this ratio is termed the *modulus of elasticity,* and we have moduli of elasticity in tension, compression, and shear. The moduli in tension and compression are usually equal. The modulus for either direct stress is known as *Young's modulus,* and is denoted by the letter E.

According to notation used in this work, we have the following for direct stresses:

P = end axial load;
l = length of bar;
A = area of cross-section;
e = longitudinal deformation;
ϵ = unit longitudinal deformation;
S_t or S_c = unit stress of tension or compression;
E = modulus of elasticity.

Then $$E=\frac{\frac{P}{A}}{\frac{e}{l}}=\frac{S_t}{\epsilon} \text{ or } \frac{S_c}{\epsilon}. \quad (1)$$

5. Longitudinal and Lateral Deformation under Direct Stress.—When a body is subjected to a direct stress, either tension or compression, it undergoes a certain amount of lateral as well as longitudinal deformation. The ratio of lateral to longitudinal deformation is called Poisson's ratio, denoted by λ. The values of this ratio for some of the more common materials are as follows: *

Glass	0.2451	Brass	0.3275
Steel	0.2686	Delta-metal	0.3399
Copper	0.3270	Lead	0.4282

6. Volumetric Deformation.—If the length (l) of a body is increased by ϵl, its lateral dimensions are decreased in accordance with Art. 5 and the new volume of a rectangular bar having lateral dimensions of b and d would be

$$l(1+\epsilon)\cdot b(1-\epsilon\lambda)\cdot d(1-\epsilon\lambda)=lbd(1+\epsilon-2\epsilon\lambda).\dagger$$

But the original volume was lbd, hence the change of volume is $lbd(1-2\lambda)\epsilon$, and the relative change is $lbd(1-2\lambda)\epsilon$, divided by the original volume, or $(1-2\lambda)\epsilon$.

If we now apply an equal direct tension in the direction of b, we would increase this dimension by ϵb, and the volume by $lbd(1-2\lambda)\epsilon$ as before. A similar result is produced by a tensile force in the direction of d; hence, for a direct tensile force in all three directions, the volume will be increased by $3(1-2\lambda)\epsilon$ times its original volume, and each dimension by $(1-2\lambda)\epsilon$ times its original value. For a compressive force in all directions the volume will be diminished in the same ratio.

The volumetric modulus of elasticity for equal stresses in all directions will be equal to the unit stress divided by the relative strain $3(1-2\lambda)\epsilon$ or, if E_v = volumetric modulus, $E_v=\frac{S}{3(1-2\lambda)\epsilon}$.

But $\frac{S}{\epsilon}$ is the value of Young's modulus or E, hence,

$$E_v=\frac{E}{3(1-2\lambda)}. \quad (2)$$

If, for example, $\lambda=\frac{1}{4}$, then $E_v=\frac{2}{3}E$.

---

[*] Taken from Wertheim and given in the Report of the French *Commission des Méthodes d'Essai des Matériaux de Construction*, 1895, Vol. 3, p. 6. For λ for concrete and stone see Art. 521 and 271.

[†] Omitting terms containing ϵ^2 and ϵ^3, as ϵ is a small quantity.

7. Shearing Deformation and Shearing Modulus of Elasticity.—Let *ABCD*, Fig. 1, represent a very small element of a body subjected to the shearing stresses *V*. The dimensions perpendicular to the plane of the paper may be taken as unity. For equilibrium the shearing stresses *V* must be equal on all four faces, the couple formed by the two vertical forces being balanced by that formed by the two horizontal forces. The unit shearing stress will be $\frac{V}{l}=S_s$.

Taking a diagonal section on the line *AC*, it will be found that the stress on this section will be purely tensile and equal in intensity to the shearing stress. That is, $S_t=S_s$. Likewise on the diagonal *DB*, the stress is compressive and has an intensity of $S_c=S_s$. The element will be deformed into a rhombus, as shown in Fig. 2. Assuming the diagonals to retain their original directions, each side will be deflected through an angle θ, and the total change of angle of each apex of the original figure will be 2θ. This angular change is a measure of the unit shearing deformation, and the unit shearing stress S_s divided by this relative deformation, is called the *modulus of elasticity in shear*. Or,

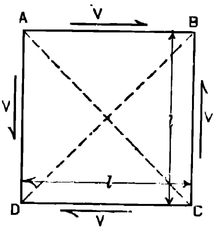

FIG. 1.

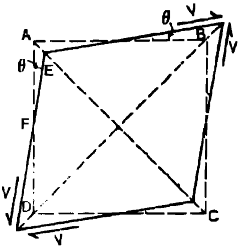

FIG. 2.

$$E_s=\frac{S_s}{2\theta}. \qquad (3)$$

The value of θ can be calculated by a consideration of the effect of the direct tensile and compressive stresses S_t and S_c. The tensile stress S_t acts to increase the length along the diagonal *DB* by the amount $\frac{S_t l}{\cos 45^\circ E}$, and to shorten the diagonal *AC* by the amount $\frac{S_t l}{\cos 45^\circ E}\lambda$ where $\lambda=$ Poisson's ratio. The compressive stress S_c causes a similar effect. The total lengthening of diagonal *DB* and total shortening of diagonal *AC* will then be equal to $\frac{S_s l}{\cos 45^\circ}\,\frac{(1+\lambda)}{E}$.

From Fig. 2 the angle θ (in radians) is practically equal to $\frac{AE \cos 45}{AF}$; or, substituting from the preceding values, we have

$$\theta=\frac{S_s(1+\lambda)}{E}. \qquad (4)$$

The modulus of elasticity in shear is therefore equal to

$$E_s = \frac{S_s}{2\theta} = \frac{S_s E}{2S_s(1+\lambda)} = \frac{E}{2(1+\lambda)}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

This equation gives the theoretical relation between the shearing modulus and the modulus in direct stress.

In practice, it is difficult to determine experimentally the exact value of E_s corresponding to the theory herein given, on account of the presence of other stresses than those here considered and the fact that the shearing stresses vary from point to point in a test specimen. However, experimental values correspond approximately with the theoretical values determined by the above equation.

In the case of steel, for example, $E = 30{,}000{,}000$ lb. per square inch, $\lambda = .27$, hence from Eq. (5) $E_s = \frac{30{,}000{,}000}{2.54} = 11{,}800{,}000$. Bauschinger found from tests on round bars $E_s = 13{,}600{,}000$, and from tests on square bars $E_s = 11{,}500{,}000$ lb. per square inch.

8. Characteristic Behavior of Materials under Stress.—Materials differ very widely in their behavior under stress. Some of these differences, such as elasticity and plasticity, have already been mentioned. Other common characteristics are indicated by the following terms: ductile, brittle, stiff, flexible, tough, malleable, and hard.

Ductile materials are capable of being drawn out without necking down. Wrought iron, soft steel, and copper are ductile metals.

Brittle materials have little or no plasticity. Such materials show little deformation beyond the elastic limit, and will therefore fail suddenly and generally without warning. Cast iron, stone, brick, and concrete are materials that are comparatively brittle, but which have, however, a considerable amount of plasticity.

Stiff materials have a high modulus of elasticity, that is, a high ratio of stress to deformation. They deform little for a given load. Another sense in which this word is used is to indicate a material with relatively high elastic limit. Thus, a spring made of hard steel will have the same deformation per unit of load as one made of soft steel (the values of E being the same), but it will carry a greater load than the spring of soft steel, as the elastic limit is higher. It is therefore often called a *stiffer* spring. Technically speaking, the two have the same degree of stiffness.

Flexible materials will bend considerably without rupture. They have a low modulus of elasticity, or a low elastic limit and considerable ductility or plasticity beyond that limit. Willow and hickory are flexible woods.

Tough materials will withstand heavy shocks or will absorb a large amount of energy. Toughness is dependent upon strength and ductility or strength and flexibility. Mild steel, wrought iron and hickory are tough materials.

Malleable materials can be hammered into thin sheets without rupture. Malleability is dependent upon the ductility and softness of the metal. Copper is very malleable, wrought iron and soft steel are somewhat malleable at ordinary temperatures but may be more easily worked at a red heat.

Hard materials offer high resistance to scratching or denting. They are not necessarily of great strength. White cast iron and chrome steel are such metals. Materials which offer high resistance to abrasion are also called hard, although they may not be highly resistant to indentation. Manganese steel is an example of such material.

MATERIALS UNDER TENSILE STRESS

9. General Phenomena Accompanying Tensile Tests.—When a body of uniform cross-section is subjected to the action of a tensile force, it is elongated in the direction of this force by a proportionate amount equal to the average force per square inch divided by its modulus of elasticity; thus

$$\frac{e}{l} = \text{proportionate elongation} = \frac{S}{E},$$

where e = total elongation, S = force or stress per unit area and E = modulus of elasticity (Young's modulus). At the same time its lateral dimensions are reduced in accordance with Poisson's ratio, as described in Art. 5. The rate of elongation in the direction of the force, and contraction in its transverse dimensions, continues in strict proportion to the amount of the external force, until the elastic limit is reached, when both the longitudinal elongation and the transverse contraction begin to increase at a more rapid rate, until finally, with the more ductile metals, the condition of perfect plasticity is reached, and the body elongates under a constant force, while the lateral dimensions reduce more and more, until rupture finally occurs.

If the external force or load, in pounds per square inch, be represented by vertical ordinates, and the corresponding elongations be represented by horizontal abscissæ, then the action of the specimen under test may be indicated by what is known as a stress-diagram, the vertical coordinates representing stress, and the horizontal coordinates the corresponding deformations. In Fig. 3 such stress-diagrams are shown for zinc, cast iron, wrought iron, and steel. These lie on the upper side of the horizontal axis. If the same materials were to be subjected to compressive external forces, corresponding stress-diagrams might be drawn in opposite directions, that is to say, downward and to the left, as indicated in Fig. 3, below the horizontal axis.

In Fig. 4 are shown portions of these same tensile diagrams with the deformation scale largely magnified, so as to bring out more clearly the characteristics of the various curves for small deformations. It will be noted that the diagram for zinc is curved almost from the beginning; the diagram for cast iron is straight for only a short distance; the diagrams for wrought iron and steel are straight until the stress has reached 50 to 60 per cent of the ultimate strength. The diagrams for zinc and cast iron are typical for materials of a non-homogeneous nature. Stone, brick, cement, concrete and some of the brasses and bronzes behave in much the same way, as shown by the diagrams in Art. 272, 300, 519 and Ch. XXVI. Many of the more ductile metals behave in a manner similar to the wrought iron and soft steel; when the point of plasticity is reached (Y.P.), a considerable deformation occurs with little or no increase of load, thus giving a horizontal notch in the curve.

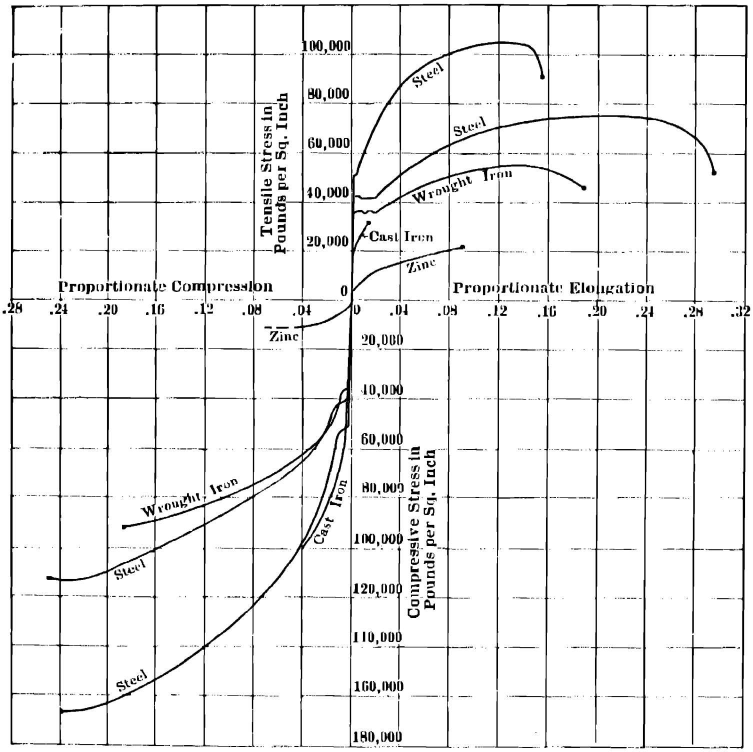

FIG. 3.—Typical Stress-diagrams of Rolled Zinc, Cast Iron, Wrought Iron, and Steel in Tension and Compression.

10. The Significant Results of a Tensile Test.—There are eight significant results of a tensile test, namely:

1. Elastic limit.
2. Modulus of elasticity.
3. Ultimate strength.
4. Percentage elongation.
5. Percentage reduction in area.
6. Modulus of resilience.*
7. Energy of rupture.*
8. Character of fracture.

11. The Elastic Limit and Its Indices.—In Art. 3, the elastic limit was defined as the maximum unit stress below which the material would fully recover its form on removal of the load. Since the determination of this critical stress involves a large number of applications and removals of loads, each somewhat larger than its predecessor, such determinations are tedious and rarely made. Approximations of the elastic limit are obtained from the proportional limit, yield point, and yield strength. The *proportional limit*, Fig. 4, a very close approximation of the elastic limit, is the maximum unit stress within which the ratio of stress to deformation is constant. Since the stress-diagram departs from a straight line at the proportional limit, the latter may be determined from a large-scale diagram. This value is often reported as the elastic limit.

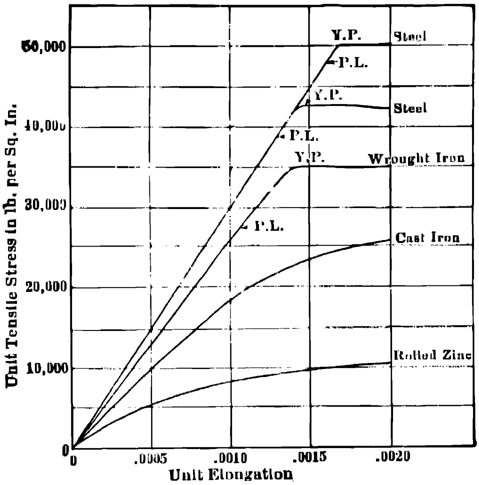

Fig. 4.—Typical Tensile Stress-diagrams for Rolled Zinc, Cast Iron, Wrought Iron and Steel to Enlarged Scale

In materials like timber, stone, and concrete, the elastic limit is low, since these materials show small permanent deformations or sets after low loads and exhibit stress-diagrams which curve near the origin. For most metals, there is little or no set at low loads, the lower portion of the stress-diagram is sensibly straight, and the elastic limit and proportional limit are relatively high. However, the exact point of departure of the curve from a straight line is difficult to determine, and its location depends on the precision of the observations and to some extent upon the scales of the stress-diagram. The proportional limit is not, therefore, quickly determined. Hence in routine testing of wrought iron and structural steel the customary practice is to determine the *yield point*, the first unit stress at which deformation continues without an increase in load. The yield point is always higher than the elastic and proportional limits, commonly 5 to 15 per cent in structural steel.

---

* Defined on p. 40.

To arrive speedily at a rough estimate of the elastic limit of metals like copper, aluminum, and their alloys, having no yield point, determinations are now made of the *yield strength*. The yield strength is the unit stress corresponding to a small prescribed set. Thus, if a set of 0.001 in. per in. is specified, the yield strength may be found from the intersection of a line drawn 0.001 in. per in. from and parallel to the initial portion of the stress-diagram (see Y.S. Fig. 5). The proximity of the yield strength to the proportional limit is dependent upon the magnitude of the set prescribed.

Specifications for acceptance tests of metals sometimes require that the metal must develop a certain *proof stress* within a certain elongation. For example, structural steel might be required to sustain a proof stress of 30,000 lb. per sq. in., with a unit elongation not greater than 0.0012.

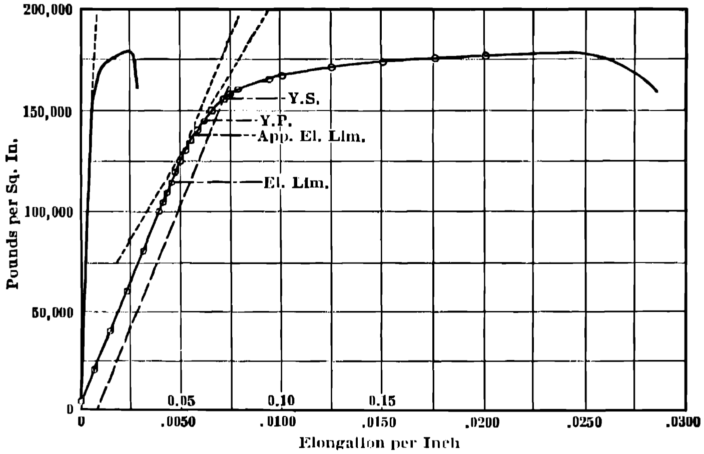

FIG. 5.—Stress-diagram of Hard-drawn Steel Wire. (*Tests of Metals*, 1890.)

The original author of this work proposed that, in view of the difficulty of determining the elastic limit, *an apparent elastic limit* be taken *on the stress-diagram at a point at which the rate of deformation is* 50 *per cent greater than at the origin.* This apparent elastic limit would approximate the yield point in materials having such a point and would give a reasonable elastic limit for such materials as cast iron or hard steel, for which this diagram shows a very gradual curvature. This meritorious criterion would accomplish the following results:

1. It always fixes one and the same well-defined point.
2. This point always corresponds to a permanent deformation so small as to be, for many practical purposes, the elastic limit.
3. It is equally applicable to all kinds of tests, whether on specimens or structures, where deformations can be correctly measured.

Although the 50 per cent increase in the rate of deformation is purely arbitrary, it is not large enough to fix a point having an appreciable set; but it is large enough to fix a well-defined point on the diagram.

Figure 5 illustrates the relation between the apparent elastic limit as here proposed and the elastic limit and yield point.

12. The modulus of elasticity is determined from the initial slope of the stress-diagram within the elastic limit. In finding this slope, the tangent of the angle between the curve and the deformation axis can be easily evaluated by using a multiple of unity as the deformation value. Thus, entering Fig. 4 with a unit deformation of 0.001, the corresponding unit stress for steel is 30,000 lb. per sq. in.; hence $E = 30,000 \div 0.001 = 30,000,000$ lb. per sq. in. If an initial load is used, the slope may be easily read from a line drawn parallel to the original curve.

In materials having a curved diagram almost from the beginning, the modulus of elasticity is not so readily defined or determined. For very small unit stresses, it is taken as the slope of the tangent at the origin. Sometimes, however, as in concrete, the actual working stresses lie somewhat above the straight portion of the diagram; there will actually be a slight permanent set in such material under working loads. In such a case it is desirable to consider the modulus of elasticity to be the slope of the secant line (see Fig. 17, Chapter XIV) drawn from the origin to the point in the curve corresponding to the unit stress (S) in question. The slope of this line is then called the modulus of elasticity at the unit stress S. This use of the term modulus is especially applicable to problems in reinforced concrete.

13. The ultimate strength of a specimen under tension is obtained by dividing the maximum load, which occurs at or just before rupture, by the original cross-sectional area. It is shown as the maximum ordinate on the stress-diagram. For plastic metals the cross-section at fracture is a third to a half the original area. Therefore, owing to such cold working of the metal, the actual breaking strength, found by dividing the breaking load by the final area, is two to three times ~~the~~ ultimate strength.

14. The percentage of elongation is found by dividing the increase in the gage length measured across the fracture by the original gage length. In the United States and England the standard gage length is usually 8 in. In Germany and France it is 20 cm., nearly the same length. The elongation of a specimen of plastic metal may be divided into two portions: (a) the elongation which is distributed uniformly along the length; (b) that part which is non-uniformly distributed in the vicinity of the fracture. Thus in Fig. 6 all specimens of one set were originally of the length indicated by the untested specimen which stands on the left side of each group. The specimen next adjoining it on the right has been stretched to the limit of the elongation indicated in (a) above, or until there is an indication of a local reduction of area. The right-hand specimen in each group shows the local elongation and reduction, but the specimen has been removed from the testing-machine before rupture occurrred. The middle specimen of each group has been tested to the ultimate strength of the material, since, when the specimen begins to reduce locally, the ultimate strength has been passed, and the stress diagram begins to fall, or it is developed under a diminishing load.

By the amount, therefore, that the right-hand specimen in each of these groups is longer than the middle specimen of the group, by so much has the length been increased by the load drawing out on the section where failure will finally occur. The first elongation, therefore, is that portion which is uniformly distributed over the specimen, and the second is that which is concentrated in the vicinity of the final failure. Both of these elongations are, however, measured and included in the total elongation, from which the percentage of elongation is determined. The total elongation is obtained after rupture has occurred, by placing the two ends together and measuring the distance between the primitive gage-marks. In the case of specimens having shoulders at their ends the gage-marks should be at least $\frac{1}{2}$ in. inside of the shoulder, since the metal adjacent to the shoulder does not elongate fully, because of the strengthening effect of the enlarged cross-section at the ends.

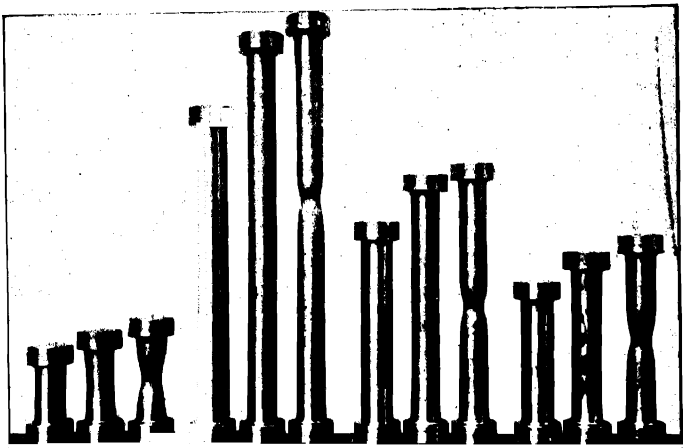

Fig. 6.—Showing the Necking-down Action of Steel Bars before Rupture. (Tetmajer, vol. 4.)

It will at once be apparent from a study of these specimens that the (*b*) elongation, or that which is locally developed in the vicinity of final rupture, is nearly the same in all these specimens; whereas the (*a*) elongation, or that which is uniformly distributed over the specimen, is always directly proportional to the length. The total elongation therefore, will not be proportional to the length. In other words, the percentage of total elongation will be greater for the short specimen than for the long ones. This shows the necessity of using standard lengths of these specimens when the percentage of elongation is to be found.

The percentage of elongation is the result which indicates the ductility of the material, this being one of the most important qualities of the metals used in structural designing.

15. The reduction of area of cross-section is found by determining the area of the broken cross-section, subtracting this from the original area of cross-section, and dividing the difference by the original area. This is not so important an indication or result as the others described above, but it is customary to determine it, and to add it to the record. For the ductile metals this reduction of area may be as much as from 50 to 60 per cent of the original cross-section.

16. Failure in Tension.—Illustration of the types of failure common to brittle and ductile metals may be seen in Fig. 6, Chapter III. In general, for ductile homogeneous materials the tensile elastic limit is reached when the shearing stress on any plane through the bar reaches the shearing elastic limit. Evidence of this is seen in the appearance of fine lines called Luders lines on the surface making angles of approximately 45° with the axis of the test-piece. The fracture of a ductile bar, like soft steel, shows a full cup and cone, the base angle of the latter also being about 45°. In the medium steels the cone is truncated, showing that the failure is partly shear and partly tensile. For very hard steels and other brittle materials the fracture is square across, showing that failure is due to tension.

Since the unit stress in shear on a 45° plane is $\frac{P}{2A}$ it follows that we may expect a cone or truncated cone fracture whenever the ultimate shearing strength is less than half of the *true* tensile strength * (i.e., tensile load

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* If we cut an oblique section through a bar under tension or compression and place upon the cut section equilibrating forces normal and tangential to it, the magnitude of the tangential component is $P\cos\theta$ and the intensity of shear stress is

$$s_s = P\cos\theta \div \frac{A}{\sin\theta}, \quad \text{or} \quad S_s = \frac{P}{2A}\sin 2\theta;$$

where P = end load, A = area of cross-section, and θ = inclination of cut to axis of bar $S_s = \frac{P}{2A}$, a maximum value when $\theta = 45°$.

divided by minimum area). When the true ultimate tensile strength is less than twice the shearing strength a square break will obtain.

Peculiarities in fracture will be further considered under tests of various materials.

MATERIALS UNDER COMPRESSIVE STRESS

17. Two Classes of Engineering Materials.—Engineering materials may be divided into two general classes, according to their manner of failure in compression.

Plastic or viscous materials are those which will flow without showing any other indication of failure.

Brittle or comminuible materials are those which will crush to a powder, or crumble to pieces, or fail by shearing on definite angles under a compressive load.

In the former class are such materials as wrought iron, soft and medium steel, the alloys, lead, copper, zinc, and the like. Of the latter class are cast iron, hard or tempered steel, brick, stone, cement, etc. The laws of failure of these two classes are very different, and they will, therefore, have to be discussed separately.

18. Crushing Strength of Plastic or Viscous Materials.—There is no such thing as an "ultimate strength," in compression of a plastic body. There is, however, a definite yield point, the same as in tension. Beyond this limit the material simply spreads, and increases the area of its cross-section indefinitely under an increasing load, as shown in Fig. 11, Chapter III. This elastic limit in compression for wrought iron and steel is, fortunately, about the same in pounds per square inch as the elastic limit in tension. It is not customary, therefore, to test such materials in compression, but to assume that they have the same elastic limit in compression which they are found to have in tension.

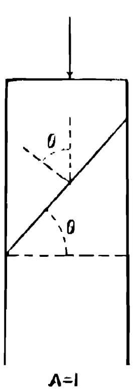

FIG. 7.

19. The Law Governing the Strength in Compression of a Brittle or Comminutible Material.—Experiments show that all such materials when subjected to a compressive load fail by shearing on certain definite angles. The resistance to movement along these angles is made up of two parts: first, the strength of the material to resist shearing; and second, the frictional resistance to motion along this plane. The sum of these two resistances must equal the shearing component of the load imposed when resolved along the shearing plane. To find what this angle should be, we may equate the two resistances here described with the shearing force, and find the angle of rupture, the determining condition being that this angle shall be that which offers the least total resistance to failure under a crushing load. This angle may be found in the following manner:

Let S_s = shearing strength of the material per square inch;
A = area of prism = 1 sq.in.;
θ = angle of rupture;
S_c = crushing load per square inch.

The tendency to slide on the plane of rupture is $S_c \sin \theta$.

The resistance to sliding is $S_s \sec \theta + fS_c \cos \theta$, where f is the coefficient of friction = tan ϕ, where ϕ = angle of repose. Hence, at failure,

$$S_c \sin \theta = S_s \sec \theta + fS_c \cos \theta. \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

It is evident that the angle of rupture will be such as to cause failure under the least load; hence if θ be taken as the independent variable, we shall have at rupture

$$\frac{dS_c}{d\theta} = -S_s(\cos^2 \theta - \sin^2 \theta + 2f \sin \theta \cos \theta) = 0,$$

or

$$f = -\frac{\cos^2 \theta - \sin^2 \theta}{2 \sin \theta \cos \theta} = -\frac{\cos 2\theta}{\sin 2\theta} = -\cot 2\theta. \quad . \quad . \quad . \quad . \quad (7)$$

Whence, since $f = \tan \phi$, we have

$$\tan \phi = -\cot 2\theta = -\tan (90^\circ - 2\theta) = \tan (2\theta - 90^\circ),$$

or

$$\phi = 2\theta - 90^\circ \quad \text{and} \quad \theta = \frac{90^\circ + \phi}{2} = 45^\circ + \frac{\phi}{2}. \quad . \quad . \quad . \quad . \quad . \quad (8)$$

That is to say, *the angle of rupture is 45° plus one half the angle of repose.*

If the friction had been omitted, we should have had

$$S_c \sin \theta = S_s \sec \theta; \quad \text{whence} \quad \frac{dS_c}{d\theta} = -S_s (\cos^2 \theta - \sin^2 \theta) = 0;$$

whence $\cos^2 \theta = \sin^2 \theta$, or $\theta = 45^\circ$. . . . . (9)

It has been customary to neglect the friction, and to state that the planes of rupture make this angle of 45° with the horizontal; * but the actual plane of rupture, when the specimen has sufficient height, is about 55° with the horizontal, or 35° from the direction of the applied load. (See Fig. 13, Chapter III, showing tests on sandstone made by Prof. Bauschinger.) Mr. Charles Bouton has shown † that the theoretical angle of rupture is borne out in practice with many kinds of materials. (See Fig 12, Chapter III, for photographic views of crushed specimens of cast-iron cylinders of various heights, showing angle of rupture.)

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* *Coulomb* is responsible for this theory, while *Navier* has given the true analysis. Most writers, including Rankine, have followed Coulomb, however.

† In a thesis for the degree M.S. at Washington University, 1891, entitled *Theory and Experiments on the Laws of Crushing Strength of Short Prisms.*

The following table gives the results of Mr. Bouton's determinations of the theoretical and the actual values of this angle:

Material.	Number of Experiments.	Observed Angle of Rupture. θ	Observed Angle of Repose. ϕ	Theoretical Angle of Rupture. $45°+\frac{\phi}{2}$	Differences.
" F." cast iron	24	54°.8±0°.2	20°.6	55°.3	−0°.5
" C. W." cast iron	24	55 .0±0 .2	16 .9	53°.4	+1 .6
Limestone	4	62.2	33 .4	61 .7	+0 .5
Asphalt paving mixture	3	59.7	27 .3	58 .6	+1 .1
Milwaukee brick	4	58.2	27 .0	58 .5	−0 .3

The " F." cast iron was good foundry iron, having a tensile strength of 22,000 lb. per square inch and a modulus of elasticity of 14,500,000 lb. per square inch; the " C. W." iron was car-wheel iron, having a tensile strength of 20,000 lb. per square inch and a modulus of elasticity of 6,500,000 lb. per square inch, or less than one-half of the former.

20. Relation of Crushing Strength to Shearing Strength.—To show the relation of the crushing strength to the shearing strength, we have, from equation (6) in the previous article,

$$S_s = S_c(\sin\theta\cos\theta - f\cos^2\theta);$$

also, from equation (7),

$$f = -\cot 2\theta = -\frac{\cos 2\theta}{\sin 2\theta} = -\frac{\cos^2\theta - \sin^2\theta}{2\sin\theta\cos\theta}.$$

Substituting this value of f, we find

$$S_s = \frac{S_c\cos\theta}{2\sin\theta} = \tfrac{1}{2}S_c\cot\theta, \quad . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

or

$$S_c = 2S_s\tan\theta, \quad . \; . \; . \; . \; . \; . \quad (11)$$

This relation was also shown by Mr. Bouton to be well borne out in tests.

21. Column Action.—If the length of a compression member is more than ten times its least lateral dimension the member is likely to bend and the intensity of stress on the concave side of it will be augmented by the bending stress which arises from the eccentricity of the load. Strictly the liability to lateral bending is dependent primarily upon the ratio of the length of the column to the least radius of gyration of the cross-section

—the slenderness ratio. In the short columns, where the slenderness ratio is less than 125, the effect of the lateral bending is of small moment; but in long columns it may be the controlling factor. Other factors which influence column action are the condition of the ends, the homogeneity of the member, stiffness, and the position of the load with respect to the center of resistance of the column.

There are four types of end conditions which are common: Round end—the end is free to rotate; fixed end—the axis of the column has a fixed position near the column end; square end—end of column and abutting surface are perpendicular to the axis; pin end—rotation of the column end is permitted in one plane only. Fig. 8 illustrates the behavior of a column under these different end conditions. These theoretical conditions are not realized in practice. In the round and pin-end columns friction at the bearings produces restraint; on the other hand no support is sufficiently rigid to produce a fixed end.

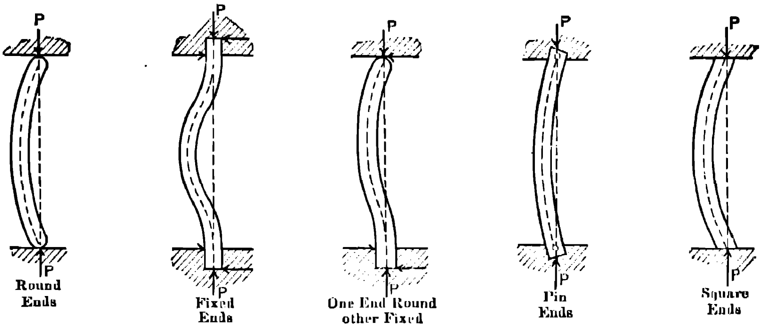

FIG. 8.—Effects of Various Types of End Conditions on the Bending of Columns.

Owing to the uncertainty regarding conditions at the ends, regarding action between parts, and regarding the position of the load with respect to the axis of the column, theoretical analyses of column action are more or less rough and the main reliance of the designer is the information gotten from tests. The more important formulæ for columns under axial loading will now be very briefly considered.

Euler's Formula.—For straight and homogeneous long columns under axial loading a rational formula is that derived by Euler

$$\frac{P}{A}=\frac{mE}{\left(\frac{l}{r}\right)^{2}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where P = critical load which produces failure of the column by lateral bending. A = area of cross-section, m = a constant depending on and conditions (theoretically $m=\pi^2$ for round ends, $4\pi^2$ for fixed ends, and

$2.05\pi^2$ for one end fixed and the other round. With conditions of practice, $m=3\pi^2$ for square ends and $1\frac{2}{3}\pi^2$ for pin ends, E = modulus of elasticity and l/r = slenderness ratio. Since the formula considers failure due to lateral flexure only and contains no term related to the compressive strength, it cannot be used to design or investigate short columns. Whenever the value of P/A computed by this formula exceeds one-third of the ultimate compressive strength of the material, Fig. 9, the result should be rejected and another column formula used. Safe loads are derived from this formula by dividing P by a suitable factor of safety.

The secant formula is the most precise column formula, but it is also unwieldy to use. For an ultimate load eccentric to both principal axes, this formula for steel columns with both ends round is

$$\frac{P}{A}=\frac{S_v}{1+\frac{e_1c_1}{r_1^2}\sec\sqrt{\frac{P}{AE}}\,\frac{l}{2r_1}+\frac{e_2c_2}{r_2^2}\sec\sqrt{\frac{P}{AE}}\,\frac{l}{2r_2}}, \quad . \quad . \quad . \quad (13)$$

where P = ultimate load, A = area of cross-section, S_v = yield point of material, e_1 = eccentricity of load from axis 1–1, c_1 = distance to outer fiber from 1–1, r_1 = radius of gyration about 1–1, l = the free length of the column, and E = modulus of elasticity. The subscript 2 refers to the 2–2 principal axis. For round end columns of structural steel with eccentricity in one plane, $\dfrac{P}{A}=\dfrac{36{,}000}{1+\frac{ec}{r^2}\sec\sqrt{\frac{P/A}{29{,}400{,}000}}\,\frac{l}{2r}}$ is an accurate formula.* For flat ends $0.56l$ should be substituted for l.

Rankine's Formula.—A semi-rational formula which holds in a very rough way for a wide range of slenderness ratios is

$$\frac{P}{A}=\frac{S}{1+\phi\left(\frac{l}{r}\right)^2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where P = ultimate load, A = area of cross-section, S = the ultimate compressive strength of a short prism, ϕ = an empirical constant, depending upon end conditions and kind of material, and l/r = slenderness ratio. For roughly determining ultimate strength of structural steel columns, S may be taken at 40,000 lb./in.^{2}, ϕ for pin ends $=\dfrac{1}{18{,}000}$, and ϕ for flat ends $=\dfrac{1}{36{,}000}$.

Straight Line Formula.—T. H. Johnson worked out a straight line formula which, in conjunction with Euler's formula, gives results approximating the breaking values got by Tetmajer from experiments on medium steel struts. The formula is

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* See Report on Steel Column Research, *Trans. A.S.C.E.*, Vol. 98, p. 1388.

$$\frac{P}{A}=S-C\frac{l}{r}. \qquad (15)$$

Here C = the slope of the tangent to Euler's curve at the point where $\frac{l}{r}=\left(\frac{3mE}{S}\right)^{1/2}$ and $\frac{P}{A}=\frac{S}{3}$, or $C=\frac{2}{3}S\left(\frac{S}{3mE}\right)^{1/2}$; P = the ultimate load; A = area of cross-section; S = ultimate strength of short prism; $\frac{l}{r}$ = slenderness ratio; and $m=\pi^2$, $1\frac{7}{9}\pi^2$ and $2\frac{1}{2}\pi^2$ for round, hinged and flat ends, respectively. Fig. 9 shows the straight line and the tangent Euler curve. Johnson's constants for steel and cast iron are given below. The data for the duralumin is from the ALCOA Structural Aluminum Handbook, in which pin ends have been considered equivalent to round ends.

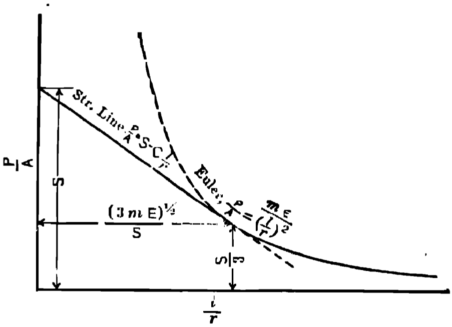

Fig. 9.

Kind of Column.	S, lb./in.^{2}	C, lb./in.^{2}	Limit of $\frac{l}{r}$.
Cast iron:			
Flat ends	80,000	438	122
Duralumin (17 S-T)			
Fixed ends	43,800	175	166
Round ends	43,800	350	83
Structural steel:			
Flat ends	52,500	179	195
Hinged ends	52,500	220	159
Round ends	52,500	284	123

The straight line type of column formula, on account of its simplicity, found considerable favor among architects and engineers; and such formulæ have been used in specifications and in the building laws.

The Parabolic Formula.—From a thorough study of the results of a large number of tests by M. Considère on small steel bars, from tests by Tetmajer on a variety of steel and iron sections, and from his own tests on timber, J. B. Johnson concluded that the strength of short columns was limited by the yield point of the material.* He proposed the following formula

$$\frac{P}{A}=S_y-f\left(\frac{l}{r}\right)^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

This is the equation of a parabola which is tangent to Euler's curve if $f=\frac{S_y{}^2}{4mE}$. The ordinate of the point of tangency is $\frac{S_y}{2}$ and the corresponding abscissa is $\left(\frac{2mE}{S_y}\right)^{1/2}$. In the above expressions P=ultimate load; A=area of cross-section; S_y compressive yield-point; $\frac{l}{r}$=slenderness ratio; $m=1.6\pi^2$ and $3.0\pi^2$ for columns with hinged and flat ends, respectively; and E=the modulus of elasticity in compression. For structural steel $S_y=36{,}000$ lb./in.^{2}, $f=0.72$ for pin ends and 0.36 for flat ends, and the limiting values of l/r for pin and flat ends are 158 and 224, respectively.

Numerous tests of rectangular columns with round ends at the Forest Products Laboratory indicate that an eighth power parabola $\frac{P}{A}=S\left[1-\frac{1}{5}\left(\frac{l}{Kd}\right)^8\right]$, and the tangent Euler curve, $\frac{P}{A}=\frac{\pi^2E}{12(l/d)^2}$, best measure the strengths of timber columns with round ends. In these expressions S is the average ultimate compressive strength of short prisms, d is the least dimension, $K=\frac{\pi}{4}\left(\frac{5E}{3S}\right)^{1/2}$, and the other terms have the significance previously stated. The ordinate at the point of tangency of these two curves is $0.8S$ and the abscissa is a value of l/d equal to K. For values of l/d less than $K/2$ the strengths of timber columns are nearly constant and equal S.

For a working formula, the above laboratory has developed the fourth power parabola and corresponding Euler tangent given in Art. 249. This fourth power parabola has a factor of safety approximating 4 and its Euler tangent a factor of safety of 3 based on the formulæ for ultimate strength of round end columns. In applying the formula to building and bridge construction, no allowance for end restraint is recommended, hence for long columns with restrained ends the actual factor of safety is somewhat greater than 3.

Of the simple formulæ for the strength of axially loaded columns, those of the parabolic type are the most accurate.

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* A conclusion which the results of recent tests on large columns at the Bureau of Standards Laboratory reaffirms. See *Engr. News*, Vol. 75, p. 190; also Vol. 76, pp. 49 and 81. See also Report on Column Research of A.S.C.E., *loc. cit.*

MATERIALS UNDER SHEARING STRESS

22. Two Manifestations of Shearing Stress.—When all the opposing external forces which act on a body lie in one plane,* but not in the same line, the resisting stresses are those of simple shear and cross-bending, without torsional stress.

When the opposing external forces do not lie in one plane the resisting stresses are those of torsional shear, with or without cross-bending and simple shear.

In any case these three kinds of stress are determined separately, as follows:

(*a*) *For Parallel External Forces in One Plane.*—The moment of resistance of the bending (direct) stresses at any transverse section is equal to the algebraic sum of the moments of the external forces on either side of that section taken about the neutral axis in that section.

The simple shearing stress on any section is equal to the algebraic sum of the transverse components of the external forces on either side of that section.

(*b*) *For Parallel External Forces Not in One Plane.*—First replace all the forces by equal parallel forces acting in the plane of the axis of the body, and by couples equal in value in each case to the force multiplied by its displacement. Then the moments of resistance and the simple shearing stresses will be the same as in the last case, and in addition there will be the moment of torsion.

The torsional moment at any transverse section is equal to the algebraic sum of the moments of the couples of the displaced forces, acting on either side of the transverse section in question.

(*c*) *For Non-parallel Forces Acting in Any Manner.*—Resolve all forces into horizontal and vertical components at their points of application, and then solve for bending moments, and torsions at any section in these two planes.

The bending moment at this section will then be the square root of the sum of the squares of the bending moments at right angles to each other.

The total shear will also be the square root of the sum of the squares of the primary shears at right angles to each other.

The total moment of torsion will be the algebraic sum of the two moments of torsion found from the two sets of forces.

23. Shearing Stress Due to Torsion.—In a solid or hollow member of circular cross-section the twisting moment produces shearing deformations which, at any transverse section, vary from zero at the axis to a maximum on the surface. If the member is not deformed beyond its elastic limit the shearing deformations vary directly as the distance from the center of the cross-section, consequently the intensity of stress varies in a like manner, Fig. 10*a*. If S_s is the intensity of stress on the outer fiber of a shaft having a radius r, the moment of stress on any element da at z distance from the axis is $\frac{S z^2}{r} da$ and the total moment of all stresses is $\frac{SJ}{r}$, where J is the polar moment of inertia of the cross-section about the axis. This is the resisting torsional moment and must equal the external twisting moment M_t, or

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* When a force is distributed over an area it is here supposed to act at the center of gravity of these force-elements.

$$M_t = \frac{S_s J}{r}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

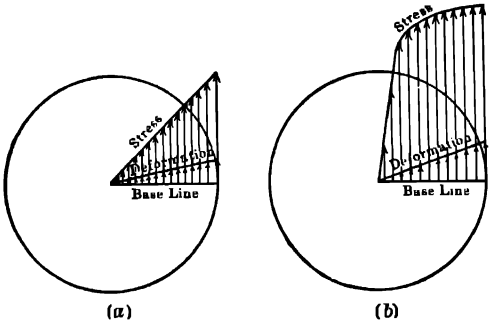

Fig. 10.—The Relation of Unit Shear Stress to Unit Deformation in a Solid Round Shaft (*a*), Stresses Within Elastic Limit (*b*), Overstrained.

For a solid round shaft $J = \frac{1}{2}\pi r^4$, and for a hollow shaft with inner radius r_1, $J = \frac{1}{2}\pi(r^4 - r_1^4)$.

Formula 17 does not hold exactly for sections other than circular. For other sections approximate values of the factor $\frac{J}{r}$ may be computed from the radius of the inscribed circle. Thus for a square shaft, with sides $= d$, the exact analysis gives $M_t = 0.2083 S_s d^3$ which is about 5.9 per cent greater than the value for a solid round shaft of diameter d. For a solid elliptical shaft of major axis a and minor axis b the exact value for $M_t = \frac{\pi}{16} S_s ab^2$. If $a = 2b$ then the exact value of M_t is double that for a round shaft of diameter b. Similarly for a rectangular shaft, $M_t = \frac{a^2 b^2 S_s}{3a + 1.8b}$, where a is the length of the long side and b the length of the short side. The greatest intensity of stress in an elliptical or rectangular shaft occurs at the ends of the minor axis.

If the shaft is deformed beyond its elastic limit the shearing deformation increases approximately as the distance of the fiber from the axis but the intensity of stress does not vary directly with the unit shearing deformation, Fig. 10*b*. Values of the ultimate shearing stress in torsion cannot, therefore, be computed from $S_s = \frac{M_t r}{J}$. Upton * has made a mathematical analysis by which the true intensity of shearing stress in a solid round shaft may be gotten as follows: In Fig. 11 the full-line curve represents the relation of unit stress S_s on the outside fiber to the unit deformation of the same fiber. In plotting this curve S_s is computed by formula 17 and ϵ_s must be determined from experiment. The true stresses are represented by ordinates to the dotted line. To find the true stress DB' corresponding to a unit shearing deformation on the surface $=AD$, draw BD perpendicular to AD, prolong the tangent at B until it intersects the S_s axis at C; then $DB'=DB-\frac{AC}{4}$. For ductile materials the shearing stress-deformation curve is approximately parallel to the deformation axis at the maximum S_s, therefore the true ultimate shearing stress is

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* See *Materials of Construction* by Upton, p. 52. (Out of print.)

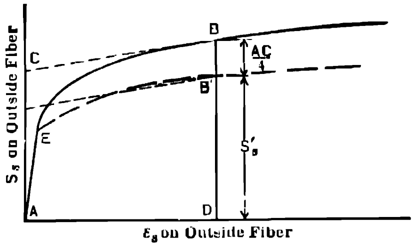

Fig. 11.—Method of Finding True Unit Shear Stress in an Overstrained Solid Round Shaft (Upton).

$$S_s'=\frac{3}{4}\frac{M_t r}{J}=.477\frac{M_t}{r^3}. \quad \ldots\ldots\ldots \quad (18)$$

For hollow shafts of ductile material in which the thickness is less than a fifth of the outer radius the intensity of shearing stress is approximately uniform throughout the cross-section when the shaft is stressed to the ultimate, therefore the maximum unit shearing stress is approximately

$$S_s=\frac{2M_t}{\pi(r+r_1)^2(r-r_1)}. \quad \ldots\ldots\ldots \quad (19)$$

24. Shearing Deformations.—As shown in Art. 7, a shearing action of external forces results in angular deformation of the body. In the case of simple shear, or where the forces lie in one plane, the angular deformation from shear is very small, the bending being mostly due to the longitudinal deformations resulting in the direct tensile and compressive resisting stresses on the two sides of the neutral plane respectively.* When the forces do not lie in one plane, or when there is a moment of torsion, the angular deformation gives rise to a twist of the body about the longitudinal axis. Thus in Fig. 12 assume the solid cylinder, anchored at O, to have a length l and a radius r. Let the torsional moment be $Pa=M_t$.

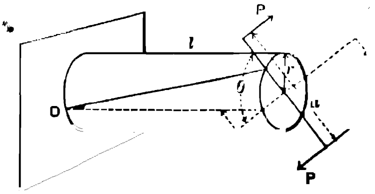

Fig. 12.

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* Shear in beams will be discussed in Art. 28.

Then $S_s=\frac{M_t r}{J}=\frac{2Pa}{\pi r^3}$. From Fig. 12 the unit shearing deformation of an outside fiber $\epsilon_s=r\theta/l$. From Art. 7 $\epsilon_s=S_s/E_s$; hence

$$\theta=\frac{M_t l}{E_s J}. \qquad (20)$$

In the above and subsequent expressions θ is in radians. Formula 20 holds for hollow or solid round shafts for stresses within the elastic limit. The angle of twist for a square shaft of side d is $\theta=7.11\frac{M_t l}{E_s d^4}$, or 43 per cent more than θ for a solid round shaft. For an elliptical section $\theta=\frac{4\pi^2 M_t J l}{A^4 E_s}$. A is the area of cross-section, and J is the polar moment of inertia. This is also an approximate formula for the twist of rectangular shafts.

Both the torsional stiffness and torsional strength of shafts of any cross-section can be accurately determined from soap film experiments (see Report 334 of U. S. National Advisory Committee for Aeronautics).

The fracture of ductile materials under torsion is generally square across. Wrought iron and some of the brasses show a rope-like twisting of the fibers before a square break ensues. Brittle materials like cast iron, stone, brick and concrete exhibit a helicoid fracture. These substances being weak in tension really fail through the secondary tensile stresses which are produced by two pairs of shearing stresses acting in planes tangent to the surface of the shaft. One of these pairs of forces acts perpendicular to the surface elements; the other pair acts parallel to the elements. Consequently on a plane at 45° with the axis of the shaft, there is produced a unit tensile stress S_t which is equal to the intensity of the shear stress S_s (Art. 7).

MATERIALS UNDER CROSS-BENDING STRESS

25. Fundamental Principles.—When a member is bent by forces applied transversely with respect to its axis, cross-bending stresses are produced. The simplest system of forces which will cause such stresses is a coplanar parallel system acting in a plane containing the longitudinal axis of the member. Such a member is called a beam. Frequently beams are horizontal, the loads are produced by gravity pulls on suspended masses and the supporting forces are upward. Under the action of these forces the beam is bent and observation shows that the fibers on its convex surface are elongated, those on its concave surface are shortened, and that there must be a plane of fibers between the convex and concave surfaces which suffers no deformation. This plane is called the neutral surface. Hence tension exists in the fibers between the neutral and the convex surfaces and compression exists in the fibers between the neutral and the concave surfaces of the beam.

It will be assumed that the beam is symmetrical, initially straight, homogeneous, of material having equal stiffness in tension and compression, that it is not stressed beyond its elastic limit by the loads, that the bending is slight, and that the plane of the external forces coincides with a plane of symmetry. If the beam is severed transversely it will be necessary, in order that equilibrium may obtain, to place a system of forces on either cut surface similar to that shown in the lower part of Fig. 13. Then from the principles of Statics we know that:

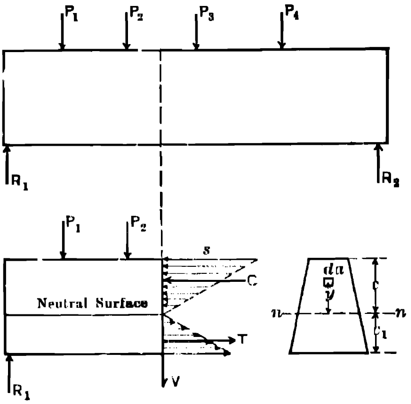


FIG. 13.

1. The vertical shear V equals the sum of the vertical forces on the left of the cut;
2. The total compression C equals the total tension T;
3. The sum of the moments of the tensile and compressive stresses on the portion shown equals the algebraic sum of the moment of the external forces to the left of the section.

From experimental evidence it is known that the unit deformations vary directly as the distance of the fiber from the neutral surface, consequently the intensity of stress varies in like manner.

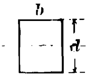
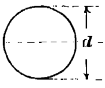
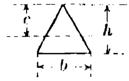
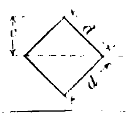
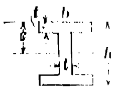
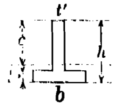
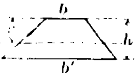
From these considerations it is easily shown that the total horizontal stress on the cut is $0=\frac{S}{c}\sum_{c_1}^{c} y\,da$, where S is the unit stress on the extreme fiber at c distance from the neutral axis, y is the distance from the neutral axis to any elementary area (Fig. 13) and the summation is taken for the entire cross-section. Since $\frac{S}{c}$ is finite it follows that $\sum_{c_1}^{c} y\,da=0$, or the neutral axis must pass through the center of gravity of the cross-section.

26. Resisting Moment Equals Bending Moment.—Taking moments of the stresses about the trace of the neutral surface $(n-n)$ and using same notation, we have $M_R=\frac{S}{c}\sum_{c_1}^{c} y^2 da=\frac{S}{c}I$. Since the resisting moment (M_R) equals the bending moment (M) there results

$$M=\frac{SI}{c}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21)$$

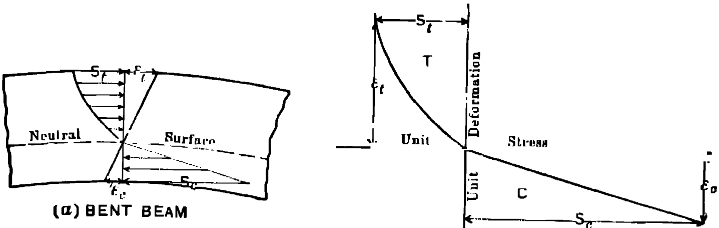
For selecting a beam to carrying a given loading S is known and M can be computed by taking the algebraic sum of the moments of all forces on either side of the dangerous section, therefore $\frac{I}{c}$ may be ascertained and the section designed. To determine the safe load for a given beam; S, I and c are known or may be computed and M is expressed in terms of the unknown load which can then be found. The third type of problem consists in finding the unit stress at a certain section of a given beam. In this problem M is computed for the given section; I and c are known and S can be determined.

Values of the moment of inertia and resisting moment for several common beam sections appear in the following table.

Form of Cross-section.	Distance of Center of Gravity, or Neutral Axis, from the Most Distant Fiber. $=c$	Moments of Inertia about the Center of Gravity of the Section. $=I$	Moment of Resistance in Terms of the Stress in the Most Distant Fiber. $=M_r=\frac{SI}{c}$
	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{1}{6}Sbd^2$
	$\frac{d}{2}$	$\frac{\pi d^4}{64}$	$\frac{\pi}{32}Sd^3$
	$\frac{2}{3}h$	$\frac{bh^3}{36}$	$\frac{1}{24}Sbh^2$
	$\frac{d}{2}\sqrt{2}$	$\frac{d^4}{12}$	$\frac{1}{6\sqrt{2}}Sd^3$
	$\frac{h}{2}$	$\frac{bh^3-(b-t')(h-2t)^3}{12}$	$\frac{bh^3-(b-t')(h-2t)^3 S}{6h}$
	$\frac{\frac{1}{2}t'h^2+t(b-t')(h-\frac{1}{2}t)}{t'h+t(b-t')}$	$\frac{bh^3-(b-t')(h-t)^3}{3}-Ac^2$	$\frac{SI}{c}$
	$\frac{b+2b'}{b+b'}\cdot\frac{h}{3}$	$h^3\left[\frac{3b+b'}{12}-\frac{(b+2b')^2}{18(b+b')}\right]$	$\frac{Sh^2}{6}\left[\frac{3(3b+b')(b+b')}{2(b+2b')}-(b+2b')\right]$

When the plane of the loads does not contain an axis of symmetry of the section, then the neutral axis is not in general perpendicular to the plane of the loads and the above formulæ are inexact. In such cases the principal axes of the section (see Moment of Inertia in Applied Mechanics) may be determined; the bending moment is resolved into the planes of these axes; and the unit stress on a given fiber is found by adding algebraically the stress due to each moment considered separately. In finding the stress due to a component moment, the neutral plane for that moment is the plane of the principal axis perpendicular to that moment. Thus if x and y are the principal axes of the section and the z-axis coincides with the longitudinal axis of the beam, $S_1 = \frac{M_y y_1}{I_x} + \frac{M_x x_1}{I_y}$. Where S_1 is the unit stress on fiber whose coordinates are x_1 and y_1 with respect to the principal axes, M_x is the component of the bending moment in the xz-plane, M_y is the component in the yz-plane, I_x is the moment of inertia about the x-axis and I_y about the y-axis.

27. Stresses in Overstressed Beams.--The flexure formula 21 does not hold for beams of materials where E_c does not equal E_t nor for beams stressed beyond the elastic limit. In the latter case the intensity of stress does not vary as the distance of the fiber from the neutral axis but follows the law of the variation of the stress ordinates to a stress-diagram in which the extreme ordinate represents the stress on the extreme fiber of the beam. If the ultimate strengths in tension and compression are unequal, the neutral axis will shift toward the stronger side of the beam as the overstressing proceeds. Thus the stress variation in a beam of cast iron, which is much stronger in compression than in tension, is illustrated in Fig 14. The unit deformation (ϵ_t) of the outside fiber in tension (Fig. 14a) corresponds to a unit stress S_t in the stress diagram of Fig. 14b. Similarly S_c for the bottom fiber and the unit stresses for other fibers may be found. If the load is increased until S_t equals the ultimate tensile strength of the cast iron, failure begins. Concrete, brick, and stone beams fail similarly; but a wooden beam, being weaker in compression, will fail first in compression.



(a) BENT BEAM

(b) STRESS DIAGRAMS IN TENSION (T) IN COMPRESSION (C)

Fig. 14.

If formula 21 be applied to find stresses beyond the elastic limit, it is evident from the foregoing that the results will be fictitious. In general the value of S_m, found when M_m is the maximum moment, will lie between the ultimate tensile and compressive strengths for the material. It is called the modulus of rupture. If the shape and size of specimen is maintained approximately constant, the modulus of rupture furnishes a good index of the strength of different grades of material. For the effect of variations in form on the modulus of rupture of cast iron beams see Art. 119.

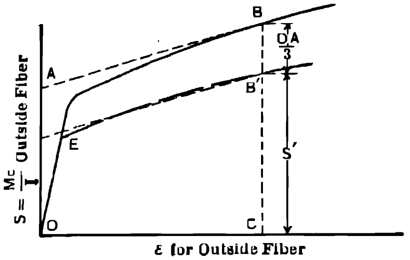


FIG. 15.—Method of Finding True Unit Stress in an Overstrained Beam (Upton).

Upton has also worked out the true value of the unit stress on the extreme fiber of an overstressed beam of rectangular cross-section.* A curve is plotted as in Fig. 15 between the computed stresses on the extreme fiber at the given section and the unit deformations of the same fiber. The true unit stress S' corresponding to a given unit deformation OC is $CB' = CB - \frac{OA}{3}$, AB being tangent to the curve OEB at B. Ordinates to the dotted curve EB' represents true unit stresses. Use of the above method necessitates measurement of the deflection and calculation of the values of ϵ, or direct measurement of the latter which is cumbersome. For ductile materials the stress-deformation curve is approximately horizontal when the maximum moment (M_m) is imposed, therefore the true stress on the extreme fiber is two-thirds of the computed stress or

$$S'_m = \frac{2}{3}\frac{M_m c}{I} = \frac{4M_m}{bd^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (22)$$

28. Variation in the Intensity of Shearing Stress within a Beam.—If a rectangular prism be cut from a beam and the forces necessary to equilibrium be placed on the cut surfaces as shown in Fig. 16, the occurrence of a horizontal shearing stress acting along the surface which parallels the neutral plane is noted. We shall now determine the average † inten-

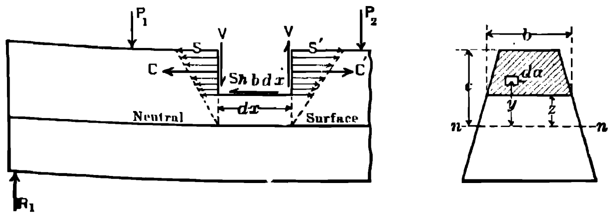


FIG. 16.

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* See *Materials of Construction*, p. 78. (Out of print.)

† The intensity of shearing stress on a horizontal plane is not always uniform unless the cross-section is rectangular.

sity of this shearing stress S_h. Let M be the bending moment at the left end of the notch, M' the bending moment at the right end, S and S' the unit stresses on the extreme fibers at the left and right end of the notch, respectively, C the total stress on the right end, C' the total stress on the left end of notch, b the breadth of the bottom of the notch, and I the moment of inertia of the cross-section about the neutral axis $n-n$. Then

$$C=\frac{S}{c}\sum_z^c yda \quad \text{and} \quad C'=\frac{S'}{c}\sum_z^c yda;$$

therefore $$C'-C=S_h bdx=\left[\frac{S'}{c}-\frac{S}{c}\right]\sum_z^c yda;$$

but $$\frac{S'}{c}-\frac{S}{c}=\frac{M'}{I}-\frac{M}{I}=\frac{dM}{I};$$

therefore $$S_h bdx=\frac{dM}{I}\sum_z^c yda;$$

and $$S_h=\frac{dM}{dxIb}\sum_c^c yda. \quad \text{Since } \frac{dM}{dx}=V, \text{ we have}$$

$$S_h=\frac{V}{Ib}\sum_z^c yda. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

In the above expression $\sum_z^c yda$ is the statical moment of the shaded area in Fig. 16 about the neutral axis n–n. Since it can easily be shown that the intensity of the vertical and horizontal shearing stresses at any point in a beam must be equal to produce equilibrium (see Fig. 1), it follows that values of the vertical unit shearing stress S_v may also be gotten by formula (23).

For a rectangular beam the intensity of the horizontal shear at any section varies, in accordance with the ordinates to a parabola, from zero at the outside fibers to a maximum at the neutral axis. For such beams the maximum value of the horizontal or vertical unit shearing stress is

$$S_h=S_v=\frac{3V}{2bd}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

where b = the breadth and d the depth of the cross-section. That is, the maximum intensity is $\frac{3}{2}$ of the mean intensity of shearing stress. Fig. 17 shows how the total shear and the intensity of the horizontal and vertical unit shearing stresses vary in a rectangular beam under uniform load.

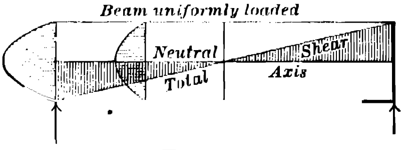

FIG. 17.

In a solid circular section the maximum intensity of shearing stress is $\frac{4}{3}$ of the mean intensity.

For an I-beam or plate girder the maximum intensity of shear stress is practically equal to the total shear at the section divided by the area of the web.

Shear in Wooden Beams.—It becomes necessary to design wooden beams for horizontal shear when the safe load in shear is less than the safe load in bending. This condition occurs only in short deep beams. Thus for a uniformly loaded rectangular beam of simple span, the safe load in bending is $W_b = \frac{4Sbd^2}{3l}$ and the safe load in shear is $W_s = \frac{4}{3}S_h bd$. If $W_s < W_b$, then must $\frac{S_h}{d} < \frac{S}{l}$. When the load is concentrated at the center, if $W_s < W_b$, then must $\frac{S_h}{d} < \frac{S}{2l}$. Here S and S_h are the allowable unit stresses in bending and horizontal shear, respectively, and b, d and l are the breadth, depth and length of the beam in the same linear units as S is expressed.

29. Deflection of Beams Due to Bending Moment.—Let Fig. 18 represent a portion of a bent beam. We shall now derive an expression for the radius of curvature and the differential equation by which the deflection of the neutral surface with respect to a set of axes may be determined. The elongation of the lower outer fiber of length dl, found by drawing ad parallel to $a'b'$, is bd. The unit elongation is $\frac{bd}{dl} = \epsilon$ and the unit stress in the fiber is $S = \epsilon E$. From the similarity of triangles oaa' and abd we have $\frac{r}{dl} = \frac{c}{db}$. Therefore $r = \frac{c}{\epsilon} = \frac{cE}{S}$. Since $S = \frac{Mc}{I}$ we have finally

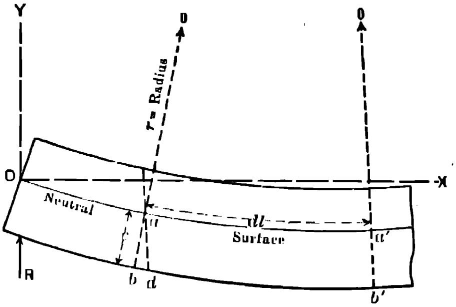

Fig. 18.

$$r = \frac{EI}{M}. \qquad (25)$$

From calculus $r = \frac{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}}$. Since in beams the curvature is slight $\left(\frac{dy}{dx}\right)^2$ is negligible compared to 1. therefore approximately $\frac{d^2y}{dx^2} = \frac{1}{r}$. Substituting in (equation 25) we have

$$EI\frac{d^2y}{dx^2} = M. \qquad (26)$$

In using this equation one must know the relation of E, I and M to the variables y and x. Commonly E and I are constants and M can be expressed in terms of the variable x. The first integration gives the equation of the slope of the neutral axis with respect to the x-axis, the second integration furnishes the equation of the neutral axis, or the elastic curve, with respect to the coordinate axes.

To illustrate the use of the above equation, we shall determine the deflection of a cantilever beam with an end load, Fig. 19. The bending moment at any section x-distance from the support is $-P(l-x)$; hence

$$(a)\quad EI\frac{d^2y}{dx^2}=-P(l-x);$$

$$(b)\quad EI\frac{dy}{dx}=-Plx+\frac{Px^2}{2}+c \qquad \left[c=0,\ \text{since } \frac{dy}{dx}=0 \text{ when } x=0\right];$$

$$(c)\quad EIy=-\frac{Plx^2}{2}+\frac{Px^3}{6}+c_1 \qquad [c_1=0,\ \text{since } x=0 \text{ when } y=0].$$

The deflection is a maximum when $x=l$.

$$\therefore\quad y_{\max}=f=-\frac{Pl^3}{3EI}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (27)$$

The moment for this loading is a maximum at the support and equals $-Pl$.

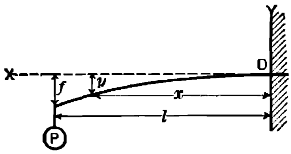

Fig. 19.

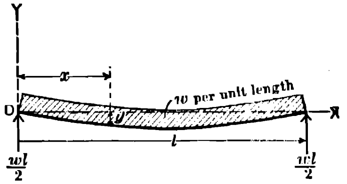

Fig. 20.

As a second illustration consider a simple beam with a uniform load, Fig. 20. The moment equation for any section x-distance from the left support is $\frac{wlx}{2}-\frac{wx^2}{2}$; hence

$$(d)\quad EI\frac{d^2y}{dx^2}=\frac{wlx}{2}-\frac{wx^2}{2};$$

$$(e)\quad EI\frac{dy}{dx}=\frac{wlx^2}{4}-\frac{wx^3}{6}+c \qquad \left[\frac{dy}{dx}=0 \text{ when } x=\frac{l}{2} \quad \therefore \quad c=-\frac{wl^3}{24}\right];$$

$$(f)\quad EIy=\frac{wl^3}{12}-\frac{wx^4}{24}-\frac{wl^3x}{24}+c_1 \qquad [x=0 \text{ when } y=0 \quad \therefore \quad c_1=0].$$

The maximum deflection is found by substituting $x=\frac{l}{2}$ in equation f; therefore

$$y_{\max}=f=\frac{-5wl^4}{384EI}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

The moment for this loading is a maximum at the center and equals $\frac{wl^2}{8}$.

The use of equation (26) becomes more tedious when the bending moment equation is a discontinuous function of x. In such cases it is generally necessary to determine the equation of the elastic curve for each portion of the beam. Elimination of the constants of integration is facilitated by remembering that the two slope equations for adjacent portions of the beam have a common value at the point of discontinuity; likewise the ordinate equations have equal values at this point. For the solution of the more complicated cases the student is referred to treatises on Applied Mechanics.

Values of the maximum moments and deflections for other beams under common types of loading appear in Table 1.

30. Deflection of Beams Due to Shear.—Besides the deflection due to bending moment there is a very slight deflection due to shear. This is of importance only in short deep beams where $l<10d$. The shearing deflection may be closely approximated by equating the energy stored by the fibers in the beam to the work done by the load in moving through a distance equal to the shearing deflection.* For a rectangular cantilever with an end load (P) the shearing deflection is $f_s=\frac{6}{5}\frac{Pl}{E_sbd}$; for a rectangular simple beam with a load (P) at the middle it is $f_s=\frac{3}{10}\frac{Pl}{E_sbd}$. For uniform loads equal to P in each of the above cases the deflection is only ⅓ as much. From the above it appears that the deflection of a rectangular beam due to shear is to the deflection due to bending as $\frac{Kd^2}{l^2}$ assuming $\frac{E_s}{E}=\frac{2}{5}$ then $K=\frac{3}{4}$ for a cantilever with an end load, 3 for a simple beam with a center load, ⅔ for a cantilever with a uniform load and 1.6 for a simple beam with a uniform load.

31. Curved Beams.—When the axis of a homogeneous beam is curved, bending of the beam produces stresses which cannot be accurately calculated by the formulæ of Art. 26. If the axis of the beam lies in a plane curve which cuts the principal axis of each cross-section and the forces act in that plane, it is sufficiently exact, however, to assume that the

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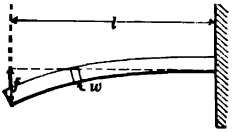
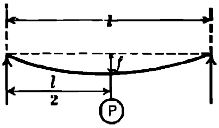
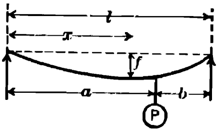
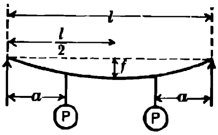
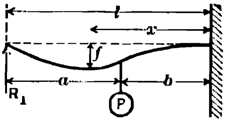
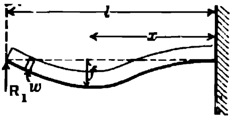
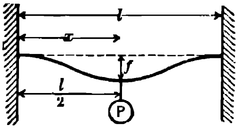
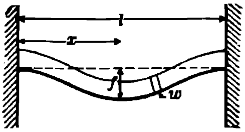
* For other cases, see Maurer and Withey's *Strength of Materials*, p. 323.

TABLE 1.—MAXIMUM MOMENTS AND DEFLECTIONS FOR BEAMS

Method of Loading.	Max. Moment, M.	Max. Deflection, f.
	$M = -\frac{wl^2}{2}$	$f = \frac{wl^4}{8EI}$
	$M = \frac{Pl}{4}$	$f = \frac{Pl^3}{48EI}$
	$M = \frac{Pab}{l}$	$f = \frac{Pb}{27EIl}\sqrt{3[a(2b+a)]^3}$ for $x = \frac{1}{3}\sqrt{3[a(2b+a)]}$
	$M = Pa$	$f = \frac{Pa}{6EI}[\frac{3}{4}l^2 - a^2]$
	$R_1 = \frac{P}{2l^3}[3lb^2 - b^3]$ $M = R_1a$, pos. $M = R_1l - Pb$, neg.	$f = \frac{Pb^2}{6EI}(l-b)\sqrt{\frac{l-b}{3l-b}}$ for $x = l\left(1 - \sqrt{\frac{l-b}{3l-b}}\right)$ if $a > 0.414l$
	$R_1 = \frac{3}{8}wl$ $M = -\frac{wl^2}{8}$ for $x = 0$ $M = +\frac{9wl^2}{128}$ for $x = \frac{3l}{8}$	$f = 0.0054\frac{wl^4}{EI}$ for $x = 0.578l$
	$M = -\frac{Pl}{8}$ for $x = 0$ $M = +\frac{Pl}{8}$ for $x = \frac{l}{2}$	$f = \frac{Pl^3}{192EI}$
	$M = -\frac{wl^2}{12}$ for $x = 0$ $M = +\frac{wl^2}{24}$ for $x = \frac{l}{2}$	$f = \frac{wl^4}{384EI}$

total deformations vary as the distances of the fibers from the neutral surface; but since the fibers are of unequal length the unit deformations, hence unit stresses, will not so vary. As a result of this condition the neutral surface does not, in general, include the gravity axis of the beam.

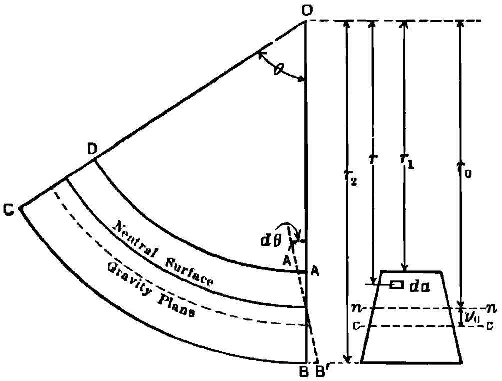


FIG. 21.

Let Fig. 21 represent a small portion of a bent beam.* Consider the end *CD* fixed and suppose *A'B'* to be the position assumed by *AB* after bending. Then the unit deformation of any fiber with cross-section *da* is $\epsilon = \frac{r d\theta - r_0 d\theta}{r\theta}$ and the unit stress $\epsilon E = \frac{(r-r_0)E d\theta}{r\theta}$. The position of the neutral axis is obtained by equating the total stress on the cross-section to zero; or $0 = \int_{r_1}^{r_2} \frac{(r-r_0)E d\theta}{r\theta} da$; since $\frac{E d\theta}{\theta}$ does not equal zero but is a constant for any given section we have

$$r_0 = \frac{A}{\int_{r_1}^{r_2} \frac{da}{r}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

The resisting moment,

$$M_R = \frac{E d\theta}{\theta} \int_{r_1}^{r_2} \frac{(r-r_0)^2}{r} da. \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

and the unit stress on the inner fiber due to a bending moment *M* is

$$S_1 = \frac{(r_1 - r_0)M}{r_1} \cdot \frac{1}{\int_{r_1}^{r_2} \frac{(r-r_0)^2}{r} da} \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

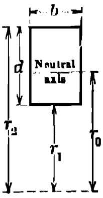
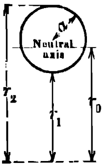
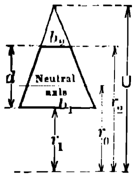
On the outer fiber,

$$S_2 = \frac{(r_2 - r_1)M}{r_2} \cdot \frac{1}{\int_{r_1}^{r_2} \frac{(r-r_0)^2}{r} da} \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

In solving equations (29) to (32) the form of the section must be known in order that the relation of *da* to *r* may be properly inserted in evaluating the integrals. M is given a positive sign when it decreases the radius of curvature. A positive sign before the result in equation (31) or (32) indicates tension. The following table contains values of r_0 and of the integral of equations (30) to (32) for rectangular, circular and trapezoidal sections.

---

* For I-, T-, or U-shaped beams of sharp curvature, having web thickness less than ½ the flange width, the radial stresses are important. See *Bulletin 195*, Univ. of Ill. Engr. Expt. Sta.

Section.	r_0	$\int_{r_1}^{r_2}\frac{(r-r_0)^2}{r}da$
	$\dfrac{d}{\log_e\dfrac{r_1+d}{r_1}}$	$b\left[d\dfrac{(r_2+r_1-4r_0)}{2}+r_0^2\log_e\dfrac{r_2}{r_1}\right]$
	$\dfrac{(\sqrt{r_1}+\sqrt{r_2})^2}{4}$	$\pi a^2\left(\dfrac{r_1+r_2}{2}-r_0\right)$
 b_2 d Neutral axis b_1 U r_2 r_1 r_0	$\dfrac{\left(\dfrac{r_2+r_1}{2}-U\right)d}{d-U\log_e\dfrac{r_2}{r_1}}$	$md\left[\dfrac{r_2+r_2r_1+r_1^2}{3}-(r_0+U)\dfrac{r_2+r_1}{2}+Ur_0\right]$ $m=\dfrac{b_2-b_1}{d}$

The accompanying table shows the ratios of unit stresses computed by eq. (31) and (32) to those gotten from $S=\dfrac{Mc}{I}$, when the curvature is sharp.*

---

* Taken from Boyd's *Strength of Materials*, pp. 327 and 333.

RATIOS OF UNIT STRESS BY CURVED BEAM FORMULA TO UNIT STRESS BY STRAIGHT-BEAM FORMULA FOR EXTREME FIBERS

$\frac{d}{r_1}$	Rectangle.		Circle.	
	Concave.	Convex.	Concave.	Convex.
0.50	1.15	.87	1.17	.86
1.00	1.29	.81	1.33	.79
2.00	1.52	.73	1.62	.70

In many practical problems a curved beam is bent by forces having components which are perpendicular to the cross-section of the member. In such cases the values of r_0 do not indicate the position of the true neutral surface, but the position which it would occupy if bending only obtained. The bending moment in such cases is computed with respect to an axis through the center of gravity of the section considered and includes the moments of all forces on one side of the given section. The unit stress on any fiber is equal to the bending stress computed as indicated above plus or minus $\frac{P}{A}$.

Example. A 4- by 2-in. rectangular bar is bent in an elliptical arc and loaded on either end with axial pulls of 3000 lb. The center of gravity of the remotest section is 5 in. from the line of action of the pulls. The inner radius (r_1) of that section is 8 in. and the outer radius (r_2) is 12 in. Find the unit stresses S_1' and S_2' on the inner and outer faces, respectively. Here $A = 8$ in.^{2},

$$r_0 = \frac{d}{\log_c \frac{r_1+d}{r_1}} = \frac{4}{0.1761 \times 2.3026} = \frac{4}{.4057} = 9.865 \text{ in.,}$$

$$b\left[d\frac{r_2+r_1-4r_0}{2} + r_0^2 \log_e \frac{r_2}{r_1}\right] = -1.08 \text{ in.}^2$$

From eq. (31) $S_1 = \frac{8-9.865}{8}\,\frac{(-5\times 3000)}{1.08} = 3240$ lb./in.^{2}

$$S_1' = \frac{P}{A} + S_1 = \frac{3000}{8} + 3240 = 3615 \text{ lb./in.}^2 \text{ tension.}$$

From eq. (32) $S_2 = \frac{12-9.865}{12}\,\frac{(-5\times 3000)}{1.08} = -2470$ lb./in.^{2}

$$S_2' = \frac{P}{A} + S_2 = +375 - 2470 = 2095 \text{ lb./in.}^2 \text{ compression.}$$

32. Strength and Deflections of Flat Plates under Normal Loads.—Symbols in the following formulæ* are:

W = total load;
w = load per unit area;
$m = 1/\lambda$, reciprocal of Poisson's ratio;
r = radius of circular plate;
r_0 = radius of circle over which load is distributed;
$2a$ = long axis of rectangular or elliptical plate;
$2b$ = short axis of rectangular or elliptical plate;
$k = b/a$, a constant;

---

[*] Formulæ 37 to 42 are from a digest of formulæ for flat plates by R. J. Roark in *Product Engineering*, July, 1936, p. 252. Formula 37 is from A. Morley's *Strength of Materials*, p. 441. Formulæ 39 to 42 are based on Timoshenko's formulæ and constants, in which $\lambda = 0.3$.

t = thickness of plate, less than $0.3r$ or $0.6b$;
S_r = maximum radial unit stress;
S_t = maximum tangential unit stress;
S_b = maximum unit stress parallel to $2b$-axis of plate;
D = maximum deflection, less than $0.2\,t$.

(*a*) *Flat Circular Plate Supported at the Circumference.*
Uniformly Loaded:

$$\text{At center, max. } S_r = S_t = \frac{3}{8}\cdot\frac{3m+1}{m}\cdot\frac{wr^2}{t^2}. \tag{33}$$

$$D = \frac{3}{16}\,\frac{(m-1)(5m+1)}{m^2}\,\frac{wr^4}{Et^3} \tag{33a}$$

Loaded over a Small Circle at Center:

$$\text{At center, max. } S_r = S_t = \frac{3(m+1)W}{2m\pi t^2}\left(\frac{m}{m+1} + \log_e\frac{r}{r_0} - \frac{m-1}{m+1}\cdot\frac{r_0^2}{4r^2}\right) \tag{34}$$

$$D = \frac{3(m-1)(3m+1)Wr^2}{4\pi m^2 Et^3} \tag{34a}$$

(*b*) *Flat Circular Plate Fixed at the Circumference.*
Uniformly Loaded:

$$\text{At edge,} \quad S_r = \frac{3}{4}\,\frac{wr^2}{t^2}, \quad S_t = \frac{3}{4}\,\frac{wr^2}{mt^2} \tag{35}$$

$$\text{At center, } S_r = S_t = \frac{3}{8}\,\frac{(m+1)wr^2}{mt^2} \tag{35a}$$

$$D = \frac{3}{16}\,\frac{(m^2-1)wr^4}{m^2Et^3} \tag{35b}$$

Loaded over a Small Circle at Center:

$$\text{At edge,} \quad S_r = \left(\frac{3}{2} - \frac{3}{4}\,\frac{r_0^2}{r^2}\right)\frac{W}{\pi t^2} \tag{36}$$

$$\text{At center, } S_r = S_t = \frac{3(m+1)W}{2m\pi t^2}\left(\log_e\frac{r}{r_0} + \frac{r_0^2}{4r^2}\right) \tag{36a}$$

$$D = \frac{3(m^2-1)Wr^2}{4\pi m^2Et^3} \tag{36b}$$

(*c*) *Elliptical Plate Uniformly Loaded.*
Edges Supported:

$$\text{At center, max. } S_b = \frac{1.25(2-k)wb^2}{t^2} \tag{37}$$

$$D = \frac{(2.34 - 1.6k)wb^4}{Et^3} \tag{37a}$$

Edges Fixed:

$$\text{At edge, max. } S_b = \frac{12wb^2}{2t^2(3+2k^2+3k^4)}. \tag{38}$$

(*d*) *Rectangular Plate Edges Supported.*
Uniformly Loaded:

$$\text{At center, max. } S_b = \frac{3wb^2}{t^2(1+1.61k^3)} \quad \ldots \ldots \quad (39)$$

$$D = \frac{2.27wb^4}{Et^3(1+2.21k^3)} \quad \ldots \ldots \quad (39a)$$

Loaded over Small Concentric Area, Radius r_0:

$$\text{At center, } S_b = -\frac{3W}{2\pi m t^2}\left[\log_e\frac{b}{r_0}(m+1) + m\left(0.4 + \frac{0.914}{1+1.6k^5}\right)\right] \quad \ldots \quad (40)$$

(*e*) *Rectangular Plate Edges Fixed.*
Uniformly Loaded:

$$\text{At centers of long edges, max. } S_b = \frac{2wb^2}{t^2(1+0.623k^6)} \quad \ldots \ldots \quad (41)$$

$$D = \frac{0.454wb^4}{Et^3(1+1.056k^5)} \quad \ldots \ldots \quad (41a)$$

Loaded over Small Concentric Area, Radius r_0:

$$\text{At center, max. } S_b = \frac{3W}{2\pi m t^2}\left[\log_e\frac{b}{r_0}(m+1) + 5(1-k)\right] \quad \ldots \quad (42)$$

RESILIENCE

33. Resilience Defined.—Resilience is the work which a body can do in springing back after a deforming force has been removed. Within the elastic limit the work of the forces deforming the body equals the energy stored in the body, that is, it equals the resilience. If a body is stressed beyond its elastic limit some of the work of the forces is spent in permanently deforming the body through sliding of the particles over one another, thus causing a loss of heat. Under the latter condition the resilience equals that portion of the total work of deformation which the body can give back upon removal of the forces.

Since work is measured by the product of the force and the distance through which the application point moves in the direction of the force, we find the work of deformation by multiplying the average stress by the total deformation. Thus the work of deformation (W) equals the resilience (K) for any unit stress (S) which is within the elastic limit and $W = K = \frac{1}{2}Pe$, where P is the maximum total stress and e the corresponding deformation.

If in the stress-deformation diagram for a body (Fig. 22) the total stresses (P) are plotted as ordinates and the displacements (e) as abscissæ, then the work of deformation (W) equals the area (measured to scales of the diagram) between the curve and the e-axis. Within the elastic limit the resilience also is measured by this area. When the elastic limit has been exceeded experiment shows that the return curve is parallel to the elastic curve—q_3q_3' is parallel to oq_2, Fig. 22. Therefore the resilience equals one-half of the maximum stress multiplied by the corresponding elastic deformation. In Fig. 22 the shaded triangle marked resilience area represents, to scale, the resilience corresponding to a maximum stress q_3d_3 and an elastic deformation q'_3d_3, the corresponding total work of the deforming stresses is measured by the area $oq_2q_3d_3$, and the energy lost through friction by the area $oq_2q_3q_3'$. The total work of deformation to rupture is often called the *energy of rupture.*

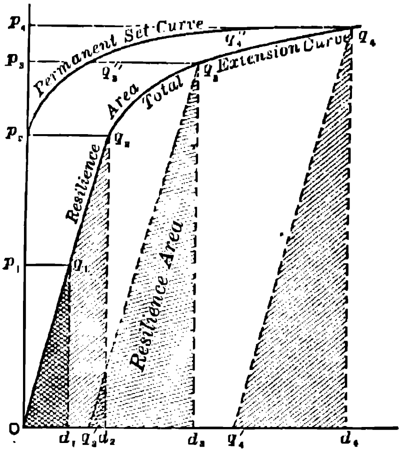


FIG. 22.

If the permanent sets be laid off from the stress-axis opposite to the corresponding stresses—p_3q_3'' equal to oq_3', p_4q_4'' equal to oq_4', etc.—then it may also be shown that the following sets of areas are equal $op_1q_1o = oq_1d_1o$, $op_2q_2o = oq_2d_2o$, $op_2q_3''q_3q_2o = q_3'q_3d_3q_3'$ and $op_2q_3''q_4''q_4q_3q_2o = q_4'q_4d_4q_4'$. Therefore the resilience equals the work of the elastic deformations.

There are three varieties of resilience commonly met: resilience of direct stress, tension or compression; resilience of cross-bending; and resilience of torsion. Values for these different kinds of resilience will now be determined. In all cases it will be noted that the resilience is directly proportional to the square of the maximum unit stress divided by the modulus of elasticity $\left(\frac{S^2}{E}\right)$, the volume (Al), and a coefficient which depends upon the kind of stress, form of cross-section and the method of loading.

34. Resilience of Bodies under Direct Stress.—Consider a homogeneous prism of uniform cross-section subjected to end axial pulls or pushes which are slowly increased until the value P is reached, $\frac{P}{A}$ being less than the elastic limit. Then the total elongation due to P is $e = \frac{Pl}{AE}$ (see eq. 1) and the total work W_p, which is equal to the resilience K, is $W_p = \frac{1}{2}Pe$. Therefore

$$K = \frac{1}{2}SA\frac{SAl}{AE} = \frac{1}{2}\frac{S^2}{E}Al. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (43)$$

The factor $\frac{1}{2}\frac{S_e^2}{E}$, where S_e is the elastic limit, is the *modulus of resilience* for a material under the direct stress considered.

It should be noted in passing that when $\frac{P}{A}$ exceeds the elastic limit, the resilience may be computed by eq. (43), but it does not equal the work of P in this case. The latter can be found from the area of the stress deformation diagram as previously indicated. It may also be approximated as follows:

For ductile materials having a stress-diagram like mild steel (Fig. 3), the energy of rupture K_r per unit of volume is approximately

$$K_r=\left(\frac{S_y+S_m}{2}\right)\epsilon_m. \quad \ldots \ldots \quad (44)$$

For materials like cast iron having a parabolic stress-diagram, approximately,

$$K_r=\tfrac{2}{3}S_m\epsilon_m. \quad \ldots \ldots \quad (45)$$

In the above S_y and S_m are the unit stresses at the yield point and maximum load, respectively, and ϵ_m is the ultimate unit elongation.

35. Resilience in Cross-bending.—Consider a homogeneous cantilever beam of uniform cross-section with an end load which is gradually increased until it reaches the value P, the latter being of such value that the fibers of the beam are not stressed beyond the elastic limit. The deflection of the free end due to bending is $f=\frac{Pl^3}{3EI}$(eq. 27) and the work (W_p) of the load is $W_p=\frac{1}{2}Pf$. Therefore the resilience $K=\frac{1}{2}Pf=\frac{P^2l^3}{6EI}$. Since the maximum unit stress, on the extreme fiber at the support is $S=\frac{Plc}{I}$ we have

$$K=\frac{S^2Il}{6Ec^2}=\frac{S^2Ar^2l}{6Ec^2}=\frac{1}{6}\frac{r^2}{c^2}\frac{S^2}{E}Al. \quad \ldots \ldots \quad (46)$$

Here r=radius of gyration and the other symbols are in accordance with previous notation. The result in eq. (46) also holds for a simple beam loaded at the middle.

Eq. (46) does not hold for stresses beyond the elastic limit because the flexure formula no longer gives the true value of S. The resilience for this case may be computed approximately from $K=\frac{P_1{}^2l^3}{6EI}$, where P_1 is the maximum load.

For beams with a uniform load the resilience may be gotten by

$$K=\frac{1}{2}\int wdxy\ * \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (47)$$

Here w is the load per unit of length, y is the deflection at any point and is expressed in terms of x, and the limits of integration include the entire beam. Thus for a simple beam with a uniform load

$$K=\frac{1}{2}\int_0^l wdx\left[\frac{wl^3x}{24}-\frac{wlx^3}{12}+\frac{wx^4}{12}\right]=\frac{w^2l^5}{240EI}.$$

For the value of y in the above, see eq. (f), Art. 29. Since $wl^2=\frac{8SI}{c}$ the resilience in terms of the unit stress on the outside fiber at the center of the beam is

$$K=\frac{4}{15}\frac{r^2}{c^2}\frac{S^2}{E}Al. \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (48)$$

In all of these discussions the resilience due to shear has been neglected because of its small effect.

36. Resilience in Torsion.—Consider a homogeneous circular shaft held at one end and twisted by a couple, the magnitude of which increases to Pa without overstressing the shaft. Evidently the work of the couple is $W_c=\frac{Pa\theta}{2}$. Substituting in this equation $\theta=\frac{M_tl}{E_sJ}$, $M_t=\frac{S_sJ}{c}$, and $J=Ar_0^2$ —where r_0 = polar radius of gyration—we have

$$K=\frac{Pa\theta}{2}=\frac{1}{2}\frac{r_0^2}{c^2}\frac{S_s^2}{E_s}Al. \quad . \ . \ . \ . \ . \ . \ . \ . \quad (49)$$

For a solid round shaft $K=\frac{1}{4}\frac{S_s^2}{E_s}Al$.

37. Resilience a Measure of Shock Resistance.—The magnitude or effect of a blow, or of a falling body, is measured by the energy stored in the moving body at the instant of impact. In the case of a body which has fallen freely in space under the action of gravity, its energy is Wh, where W is the weight of the body, and h is the distance through which the body has fallen freely. In any translation, the energy of the body is $\frac{Wv^2}{2g}$, where v is the velocity, and g is the acceleration of gravity. If a moving body, as a falling weight, is stopped by striking a fixed solid body, the energy of the moving body is spent in one or all of the following ways:

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* An alternative method of computing the resilience for such cases is afforded by the equation $K=\int\frac{M^2}{EI}dx$ where the variables are expressed in terms of x and the limits of integration cover the entire beam.

(*a*) In deforming the moving body itself, either within or beyond its elastic limit.

(*b*) In a local deformation of both bodies at the surface of contact, within or beyond the elastic limit.

(*c*) In moving the fixed body as a whole, with an accelerated velocity, the resistance consisting of the inertia of the body.

(*d*) In moving the fixed body against its external supports and resistances.

(*e*) Finally, in deforming the fixed body as a whole against the resisting stresses developed thereby.

If there is nearly absolute rigidity in all parts except in the body struck and if this yields only as a whole and not locally at the point of contact, then only can nearly all of the energy of the moving body be absorbed through deformation in the body struck. When the energy of the striking body is due principally to its mass $\left(\text{measured by } \frac{W}{g}\right)$ and only in small part to its velocity then 90 per cent or more of its energy may be absorbed by the body struck.

Assuming that all the energy of a blow is absorbed by the body struck, then it becomes apparent that the work of deformation of that body must equal the energy of the blow. Studies of the relationships of resistance to deformation under impact, where the unit stresses have exceeded the elastic limit, have, in general, shown that a given deformation under impact is accompanied by a higher unit stress than in a static, or slowly applied, loading. For the tests on soft iron wire illustrated in Fig. 23, the work of deformation in impact, as measured by the area under the impact stress-deformation curve, is about 30 per cent greater than the corresponding value for static stresses. Likewise Russell * found that the average energy of rupture of cast-iron bars tested in his pendulum impact machine (Fig. 17, Chapter II) was about 44 per cent greater than the energy of rupture under gradually applied loads. When the stresses are within the elastic limit it has been customary to assume that the moduli of elasticity for static loadings hold for impact. It has also been customary to argue from the above

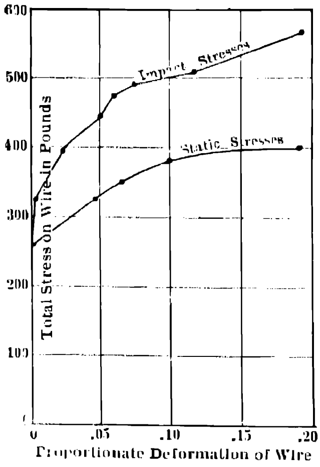

FIG. 23.—Comparison of Impact and Static Stresses when the Deformations are the Same. (*Report of French Com.*, Vol. 2, p. 344.)

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* See *Trans. Am. Soc. Civ. Engr.*, Vol. 39, p. 246.

considerations that the modulus of resilience gotten from a static test is a measure of resistance to repeated shocks or blows and that the total area of the stress-diagram (the energy of rupture) is a measure of resistance to a single blow.* In other words these quantities are considered indexes of toughness. That these conclusions do not apply, however, to all heat-treated materials is evinced by the behavior of burnt steel. This material often exhibits about as high energy of rupture in a static test as properly treated material but is far less tough. (See also Art. 711.)

A comprehensive study of the elastic portions of impact stress-deformation curves for our various building materials is badly needed in order that true value of the static modulus of resilience as an index of resistance to repeated shocks may be ascertained.

If we assume all of the energy of the blow is absorbed by the body struck and that the modulus of elasticity is independent of the speed of loading, we have for the case of direct stress under axial elastic impact

$$W(h+e)=\frac{1}{2}\frac{S^2}{E}Al. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (50)$$

Here W = weight falling, h = distance dropped, e = maximum deformation of body struck (the deformation will oscillate from a maximum to a minimum value as in a spring), S = maximum intensity of stress corresponding to deformation, E = modulus of elasticity, A = area of cross-section, and l = length.

Similarly for a beam under impact of a center load we shall have

$$W(h+f)=\frac{1}{6}\frac{r^2}{c^2}\frac{S^2}{E}Al. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (51)$$

Here f = the maximum deflection and the other quantities have usual significance. When h in either of eqs. (51) or (52) is zero, namely when the load is suddenly applied, it is easy to show that the maximum intensity of stress is twice that for a static load, W.

It may also be shown that the deformation of a bar under axial elastic impact is given by $e=e'+e'\left(1+\frac{2h}{e'}\right)^{1/2}$, where e' is the elongation due to a static load W and e that due to the impact load W. Similarly for transverse impact we have $f=f'+f'\left(1+\frac{2h}{f'}\right)^{1/2}$, where f' is the deflection due to static W and f that due to impact of W.

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* H. C. Mann in *Proc. A. S. T. M.*, Vol. 35, Pt. 2, p. 323, gives a method of evaluating the impact energy of rupture from a static stress diagram which he checked closely by tests.

MATERIALS UNDER COMBINED STRESS

38. Direct and Bending Stresses.—Consider the case of a simple beam under a transverse bending moment M and subjected to an eccentric end load P lying in a principal axis, Fig. 24, for example. Consider the force P resolved into a force along the axis of the beam and a couple Pe. Then the unit stress on the extreme fiber at the danger section is given by

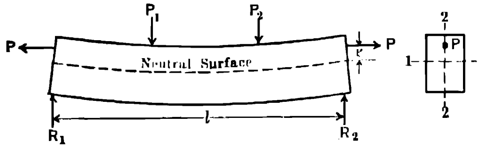

FIG. 24.

$$S=\frac{P}{A}\pm\frac{Mc}{I}. \quad \ldots\ldots\ldots \quad (52)$$

Here M is the algebraic sum of the moments due to end loading (Pe) and transverse loadings taken on either side of the section, I is the moment of inertia of the cross-section about the axis 1–1, c the distance from 1–1 to the fiber considered, A the area of the cross-section. Unless the beam is long, deflection affects the moment arm of P but little and is, therefore, not considered in computing M.

Equation (52) may also be used in designing short columns $\left(\frac{l}{r}<100\right)$ which are eccentrically load. It then reduces to

$$S=\frac{P}{A}\left(1\pm\frac{ce}{r^2}\right). \quad \ldots\ldots\ldots \quad (53)$$

Here r is the radius of gyration of the section about the principal axis which is normal to the lever arm of P.

If P does not lie on a principal axis eq. (53) does not hold. The unit stress on any fiber is then given by

$$S=P\left(\frac{1}{A}+\frac{xx_1}{I_y}+\frac{yy_1}{I_x}\right). \quad \ldots\ldots \quad (54)$$

Where x_1 and y_1 are the coordinates of the application point of the load (P) with respect to the principal axes (the x-axis and the y-axes), x and y are the coordinates of the fiber with unit stress S, I_x and I_y are the principal moments of inertia with respect to the x and y axes, respectively. Due account of the signs of x, x_1, y and y_1 must be taken in using eq. (54).

39. Shears and Direct Stress.—One of the most common cases of combined stress is direct stress with pairs of equal shears perpendicular and parallel to it. Let Fig. 25(a) represent the side elevation of an elementary rectangular parallelopiped, the thickness perpendicular to the paper being unity and the width and height dx and dy, respectively. Let the intensity of the direct stress be S and that of the shears S_s each. Then it is evident that on any oblique plane cutting the parallelopiped the total stress equals the resultant of Sdy, $S_s dx$, and $S_s dy$. Consider the total stress on the plane AC to be resolved into normal and tangential components, $S_n dz$ and $S_p dz$, respectively, see Fig. 25(*b*). We want to find the value of S_n and S_p in terms of S and S_s and then by rotating the plane AC (allowing θ to vary), determine the maximum values for these stresses. Resolving the forces on CD and AD in Fig. 25(*b*) along AC and perpendicular to it, substituting $\sin\theta=\frac{dy}{dz}$, $\cos\theta=\frac{dx}{dz}$, and reducing, we have

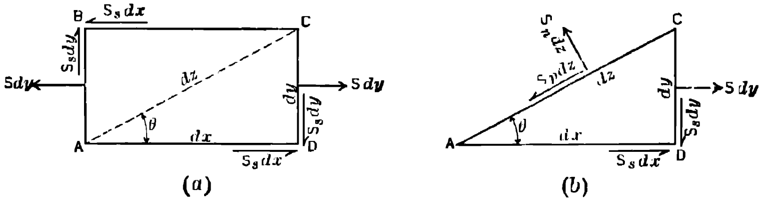

FIG. 25.

$$S_p=\frac{S}{2}\sin 2\theta+S_s\cos 2\theta, \quad \ldots \ldots \quad (55)$$

$$S_n=\frac{S}{2}(1-\cos 2\theta)+S_s\sin 2\theta. \quad \ldots \ldots \quad (56)$$

S_p is rendered a maximum or minimum when $\tan 2\theta=\frac{S}{2S_s}$; S_n is rendered a maximum or a minimum when $\tan 2\theta=-\frac{2S_s}{S}$. Substituting the corresponding sine and cosine functions in eq. (55) and (56) there results

$$S_p=\sqrt{S_s^2+\left(\frac{S}{2}\right)^2}, \quad \ldots \ldots \quad (57)$$

$$S_n=\frac{S}{2}\pm\sqrt{S_s^2+\left(\frac{S}{2}\right)^2}. \quad \ldots \ldots \quad (58)$$

When the plus sign is used in eq. (58) the magnitude of the maximum unit stress of the same kind as S is found. If the minus sign is used, the minimum normal unit stress is found; but a negative sign obtains for the entire result indicating that the stress thus gotten is of opposite kind to S. These maximum and minimum values of S_n occur at the same point on mutually perpendicular planes. There is no shear stress on either of these planes.

The unit deformation in the direction of max. S_n will be increased by the lateral deformation of min. S_n acting at right angles to the maximum value (see Art. 5 and 6) or $\epsilon_n=\frac{\text{max. } S_n}{E}+\lambda\frac{\text{min. } S_n}{E}$. Where ϵ_n is the unit deformation along maximum S_n and λ is Poisson's ratio. Substituting values of S_n from eq. (58) and changing sign of min. S_n, there results

$$\epsilon_n=\frac{S}{2E}(1-\lambda)+(1+\lambda)\sqrt{S_s^2+\left(\frac{S}{2}\right)^2}. \quad . \ . \ . \ . \quad (59)$$

If $\lambda=\frac{1}{4}$, a fair mean for metals, then

$$\epsilon_n=\frac{3S}{8E}+\frac{5}{4E}\sqrt{S_s^2+\left(\frac{S}{2}\right)^2} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (60)$$

For analyzing the internal stresses in beams and shafting eq. (57) and (58) are much used. In beams the horizontal and vertical shearing stresses provide the S_sdx and S_sdy forces of Fig. 25 and the flexure stresses make up the Sdy forces. In horizontal shafts the torsional shears in planes tangent to the shaft provide the pairs of shearing forces, and the stresses due to bending again introduce the normal forces. In vertical shafts the normal stress may be due to both direct stress (from the weight of the shaft) and lateral bending.

40. Biaxial Loading.—Fig. 26 shows an elementary parallelopiped of unit thickness under two pairs of mutually perpendicular tensile stresses. The following analysis with proper regard to sign holds, in general, whether both pairs of stresses are of like kind or not. We wish to find the value of the normal (S_n) and tangential (S_p) unit stresses on any plane such as AC. Resolving Sdy and $S'dx$ parallel to AC and perpendicular to it and substituting $\sin\theta=\frac{dy}{dz}$ and $\cos\theta=\frac{dx}{dz}$ there is obtained

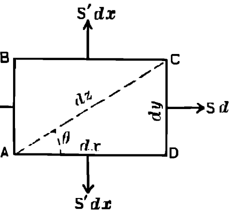

FIG. 26.

$$S_p=\frac{S-S'}{2}\sin 2\theta, \quad . \ . \ . \ . \ . \ . \ . \ . \ . \quad (61)$$

$$S_n=S\sin^2\theta+S'\cos^2\theta. \quad . \ . \ . \ . \ . \ . \ . \ . \quad (62)$$

When $\theta=45°$ $S_p=\frac{S-S'}{2}$. Note, however, that for this case the greatest value of $S_p=\frac{S}{2}$, if $S>S'$. This stress occurs in a plane parallel to S' and making an angle of 45° with S. S_n is a maximum when $\theta=90°$ if $S>S'$; when $\theta=0°$ if $S<S'$.

Eqs. (61) and (62) are of value in determining stresses in boiler shells and pipes.

41. Conditions Determining Elastic Break-down.—There has always been much perplexity concerning what factors determine the breaking down of a metal at its elastic limit. Broadly speaking, the question is, does failure begin when a certain maximum unit stress is reached, regardless of the way in which that stress is produced, or does it commence when the unit deformation reaches a certain maximum. In studying these problems experimenters * have placed specimens of ductile metals under combined tension and torsion, compression and torsion, flexure and torsion, and under biaxial loadings. The three much-used theories which have been advanced are as follows:

1. Elastic break-down begins when the maximum normal stress S_n reaches a certain value—*the maximum stress theory;*
2. Elastic failure begins when the unit deformation (ϵ_n) in the direction of the maximum normal stress reaches a certain magnitude—*the maximum strain theory;*
3. Elastic break-down begins when the maximum shear (S_p) reaches a certain magnitude—*the maximum shear theory.*

Most recent experimenters have held to the third theory, convinced that a ductile material under direct stresses, or direct and shear stresses, suffers elastic break-down when some plane in the body experiences a shear stress equal to the shearing elastic limit, and that failure ensues when the ultimate shear stress is imposed on some plane (see S_p of formula (57) and discussion in Art. 40). Becker,* however, from a very careful set of tests on thin steel tubes under biaxial loading has shown that elastic break-down will ensue if the maximum unit strain exceeds a certain value, also if the maximum unit shear stress exceeds the shearing elastic limit. In other words, for biaxial loading he found that as the ratio of $\frac{S'}{S}$ was increased the elastic limit was reached as soon as the maximum unit strain reached a certain value; when, however, as $\frac{S'}{S}$ increased, the maximum S_p $\left(=\frac{S}{2} \text{ if } S > S'\right)$ reached the shearing elastic limit before the maximum unit strain ϵ_n reached its critical value, then failure was conditioned by the maximum shear theory. The two limiting conditions for biaxial tensions are given by $\epsilon_n' = \frac{S}{E} - \lambda\frac{S'}{E}$ and $S_p' = \frac{1}{2}S$, where ϵ_n' = maximum unit elastic deformation which material can withstand and S_p' = shearing elastic limit.

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* See accounts of researches by J. J. Guest, *Phil. Mag.*, July, 1900; W. A. Scoble, *Phil. Mag.*, Vol. 12, 1906, p. 583; E. S. Hancock, *Proc. A.S.T.M.*, Vol. 5, p. 179; Vol. 6, p. 295; A. J. Becker, *Bulletin No.* 85, Univ. of Illinois Expt. Sta. Also see Art. 726.

Two additional theories of elastic failure have received considerable attention during the past decade, *the strain energy theory* and *the shear strain energy theory.* The strain energy theory of Beltrami more recently championed by B. P. Haigh states that elastic break-down begins when the quantity of strain energy stored per unit of volume exceeds the tensile modulus of resilience. If the three principal stresses are S_x, S_y, S_z, and S_e is the tensile elastic limit, the condition is

$$K_e = \frac{1}{2E}\left[(S_x^2+S_y^2+S_z^2) - 2\lambda(S_xS_y+S_xS_z+S_yS_z)\right] = \frac{S_e^2}{2E}.$$

For biaxial loading this reduces to $S_x^2+S_y^2 - 2\lambda S_xS_y = S_e^2$.

The shear strain energy theory developed by Huber and von Mises, which assumes that the elastic failure is conditioned by the arrival of the unit shear strain energy at a certain limiting value, furnishes the following criterion for K_s, the modulus of resilience in shear:

$$K_s = \frac{1+\lambda}{3E}\left[S_x^2+S_y^2+S_z^2 - (S_xS_y+S_xS_z+S_yS_z)\right] = \frac{1+\lambda}{3E}S_e^2.$$

For biaxial loading this reduces to $S_x^2+S_y^2-S_xS_y = S_e^2$.

Apparently none of the foregoing theories holds for all stress conditions. For ductile materials under biaxial loading where the principal stresses are of like kind, the principal stress or either of the strain energy theories appears to be in accord with experimental evidence. For biaxial loading with stresses unlike in sign, the principal stress theory fails; but the maximum shear, the strain energy, or the shear strain energy theories agree with observed data. In combined bending and torsion the maximum shear stress theory is the most conservative, the maximum stress theory the least conservative; but for ratios of moment to torque (M/T) above 1.0 the discrepancies in the diameters obtained by designing by any of the theories is not large.

For triaxial loading neither strain energy theory conforms to the observed facts when a ductile material is under compressive stresses of equal intensities, i.e., fluid pressure. Nevertheless, considering range of application, the shear strain energy theory, which implies that the ratio of the elastic limit in shear to that in tension is 0.58, appears to be the most dependable of the above theories.

Present evidence also indicates that the maximum stress theory is in best accord with experimental evidence on brittle materials. A good résumé of these theories and numerical comparisons may be found in *Materials and Structures*, by E. H. Salmon, Vol. 1, Chapter XVI.

CHAPTER II

MACHINES AND APPLIANCES FOR MECHANICAL TESTS

TESTING MACHINES

42. Definition.—Since it would be obviously impossible to break, or even deform considerably large specimens of strong material by the imposition of dead weights, a mechanical device called a testing machine is employed for this purpose. A testing machine may be said to consist of a base or frame which supports the crossheads used in loading the specimen, a means for applying the load, and a device for measuring it.

UNIVERSAL TESTING MACHINES

43. Classes of Universal Testing Machines.—Universal testing machines—those in which tension, compression or cross-bending tests can be made—are provided with at least one fixed crosshead against which the specimen rests and a movable crosshead by means of which the specimen is deformed. In accordance with the method employed to drive the movable crosshead, such machines may be divided into two classes, hydraulic machines and screw-gear machines. In American laboratories most of the testing machines of less than 600,000-lb. capacity are of the latter type. On the other hand the use of hydraulic testing machines in this country is rapidly increasing.

With the exception of the Emery testing machine, which belongs in a class by itself, the chief advantages of hydraulic testing machines are freedom from vibration and noise, cheapness, and simplicity of construction and operation. On the other hand, most of the testing machines of this type have one or more of the following disadvantages: leakage of fluid, variable friction at the stuffing boxes and around the ram, or inaccurate means of measuring fluid pressures.*

In American screw-gear testing machines the load is generally reduced by a system of compound levers and weighed by balancing with a poise which is moved along a graduated scalebeam. In general these machines may be made very sensitive and accurate, but when built in large capacities are more expensive than those of the hydraulic type. Owing to the vibration and noise produced by the driving mechanism employed in screw-gear machines, hand power is necessitated when very sensitive apparatus is used to measure deformations.

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* The University of Wisconsin has a 600,000-lb. universal hydraulic testing machine designed and erected by the instructional staff. As a result of calibrations the probable error of results gotten from this machine is not over 2 or 3 per cent for loads above 50,000 lb. The machine cost $3500. (See *Proc. of Am. Soc. for Testing Materials*, Vol. 10, p. 551.)

Testing machines are often called horizontal or vertical in accordance with the position in which a tension or compression specimen is held. The advantage of the former type lies in the accessibility of all parts of machine and specimen. In vertical testing machines, however, lateral bending due to the weight of the specimen is obviated.

44. General Conditions Which Should Obtain in Universal Machines.—The following considerations apply to testing machines in general:

1. The weighing apparatus should be quite independent of the loading apparatus, the former usually being fixed and the latter movable.

2. In lever machines the length of the knife-edges must be proportioned to the maximum loads in order not to be crushed down, and they should be so placed that all will receive their share of the load. They must also be so mounted as not to change the leverage by any reaction displacement which may occur. To insure this, the knife-edges must be attached to the levers, and the bearings to the platform. Clearance between knife-edge bearings and levers must be sufficient to insure against frictional resistances, which greatly impair sensitiveness.

3. The knife-edges and bearings of any beam must lie in the same straight line, and this line should lie in the gravity axis of the beam and its rigid attachments. This is especially necessary for the weighing-beam itself, so that its vertical angular movement may not disturb the counterbalancing. If the poise is moved by a cord over a pair of pulleys, this cord should be attached to the poise-hanger in this same axial line, so that the pulling of the poise may not supply a leverage on the beam to raise or lower it.

4. Manometer machines have many peculiar errors. For example, any air-bubble in the indicating liquid vitiates the results by its own change in volume under pressure. Again, the exact area of surface subjected to pressure is always uncertain.

5. The weighing apparatus should be so constructed as to be readily verified by the imposition of known weights, and the parts should be open to inspection and easily repaired and kept in order.

6. A precision of 1 in 250 has been considered sufficient.* This is a proportional error of 0.4 of 1 per cent. Also, the imposition of a load equal to one-two-hundred-fiftieth of that on the machine should produce an appreciable indication on the weighing device.

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* For methods of verification and tolerances in testing machines, consult *Standards* of American Society for Testing Materials.

7. The loading should proceed gradually and uniformly, and the rate of loading should be under perfect control.

8. The machine should be so constructed as to permit the free use of suitable appliances for measuring distortion of the specimen at all stages during tests.

9. A wide range of speeds should be available for the entire capacity of the machine. In compression tests speeds as low as 0.02 in. are often wanted, and in tension tests speeds up to 6 in. per min. find occasional use (see Art. 107).

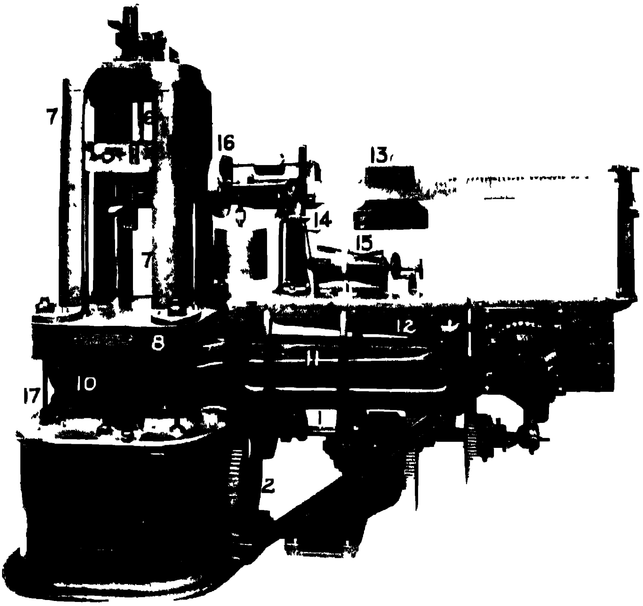

Fig. 1.—Olsen's Automatic Universal Testing Machine with Direct Motor Drive.

10. The axes of the jaws in the crossheads of the machine should be so placed that they will remain in line throughout any test provided that the specimen is properly centered in them.

11. There must be no twisting or rocking of the movable head when in motion.

45. Olsen Testing Machines.—The Olsen screw-gear machine shown in Fig. 1, affords a good illustration of the universal machines common to American laboratories. Machines similar to this are built in capacities from 30,000 to 400,000 lb.; others embodying similar principles are built in capacities up to 1,000,000 lb. Power is applied to the machine illustrated through a direct connected motor attached in the rear as shown.

The main shaft (1) transmits power to the gear (2) which, through a shaft and system of gearing, rotates four straining nuts. Each of these straining nuts bears against the underside of the bed plate of the machine (9) and revolves about one of the four vertical screws which are rigidly fastened to the pulling head (5). In this manner an upward or downward translation may be imparted to the screws and pulling head. A wide range in the rate of motion of the pulling head may be secured by means of the clutch levers (3) and (4). The pull on the specimen (6), which is held in the jaws of the crossheads by means of grooved wedges or liners, is transmitted downward through the four cast-iron columns (7) to the weighing table (8). The reaction of the straining nuts on the lower end of the screws produces an equal upward force beneath the bed plate (9). The weighing table is supported on knife-edges fastened in the compound levers (10) and (11), which in turn are pivoted on pedestals formed on the bed plate (9); a closed circuit of forces is thus produced. The force on the weighing table is reduced by the levers (10), (11), (12) and balanced by the poise (13) on the scalebeam. The poise (13) is driven by a screw running along the top of the scalebeam. The operator may drive the poise by hand through the wheel (14) or the motion of the poise may be automatically controlled by the variable speed cone drive (15) which is connected to the driving mechanism on the machine and drives the poise to the right as long as the scalebeam is up. When the beam drops an electric circuit is broken and the poise stops. The load in thousand-pound units or multiples thereof may be gotten from the graduations on the scale beam. Intermediate values of the load are read on the dial (16) which is driven by

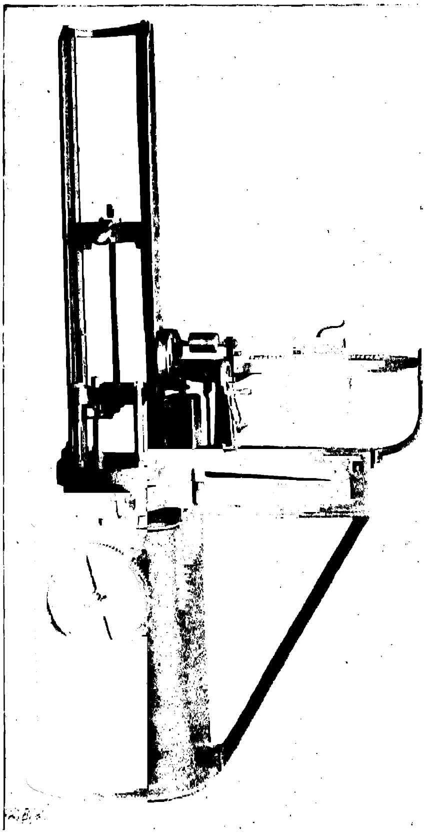

Fig. 2.—A 10,000-lb. Wire-testing Machine.

the screw actuating the poise. The energy released by breaking of a specimen is dissipated through recoil buffers (17) and cushion-seated nuts.

Compression tests are made by attaching a spherical seat to the crosshead (5) and inserting the specimen on table (8).

The machine is arranged for bending tests by placing end bearings on the table (8) (or on an I-beam extension of the table) and attaching a knife edge on the movable head (5).

For testing low-strength specimens hand-operated machines of 10,000 to 20,000-lb. capacity, Fig. 2, are very serviceable.

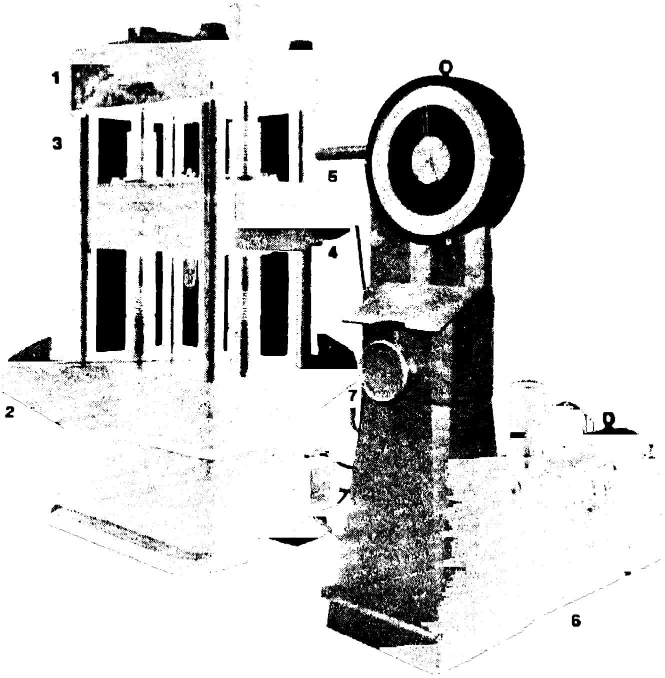

Fig. 3.—A 300,000-lb. Riehlé Hydraulic Testing Machine.

46. A Riehlé Hydraulic Universal Machine.—Fig. 3 shows a 300,000-lb. hydraulic testing machine made by American Machine and Metals, Inc. The top head (1) and the table (2) of this machine are connected by four posts (3) and are always forced upward during a test by means of the ram in the base of the machine. The lower head (4) is held to the base of the machine by the two large screws and can be adjusted to the specimen by means of the small motor (5). The ram is supplied with oil from a 6-cylinder pump (6). The rate of speed of the ram is controlled by the hand wheel (7) which turns over a graduated dial. The load is weighed by a pendulum automatic indicating device which is equipped with two weights. These weights are usually arranged to provide load ranges of

0–30,000 and 0–300,000 lb. Both the cylinder on the ram and the pressure measuring cylinder connected to the pendulum are very accurately ground and no packing is required. The measuring cylinder is rotated to reduce frictional effects to a minimum. The machine operates rapidly without disturbing noise or vibration and is very easy to handle.

47. The Emery Testing Machine.—The Emery method of weighing loads is generally considered the most sensitive yet devised.

The essential principle of this machine consists in a means of transmitting a definite percentage of the force applied to the specimen to the scale beams, and there weighing it accurately, without any friction whatever in the receiving, transmitting, or weighing parts. Hence any very small increment of the force applied is weighed with equal accuracy, whether this increment is added to a great or to a small previous load.* This is accomplished by means of an hydraulic leverage and through the use of steel plate fulcra instead of knife-edges. Thus, in Fig. 4, which is merely a schematic drawing, the load from the ram (1) is transmitted through the specimen (2) to the yoke (4), which rests against the hydraulic support (5). A pressure of equal intensity to that produced upon the liquid in the hydraulic support is transmitted to the hydraulic chamber. In principle, an hydraulic support or chamber consists of a very strong shallow metal cylinder covered by a thin diaphragm or of a plate with a thin diaphragm around the edge. The diaphragm permits a slight movement of the cover without leakage of the fluid. The total force acting against the top of the chamber (7) is to the force in the specimen as the effective area of the chamber top is to the effective area of the hydraulic support. The force on the chamber top is balanced by levers articulating elastically about thin steel plate fulcra (8)

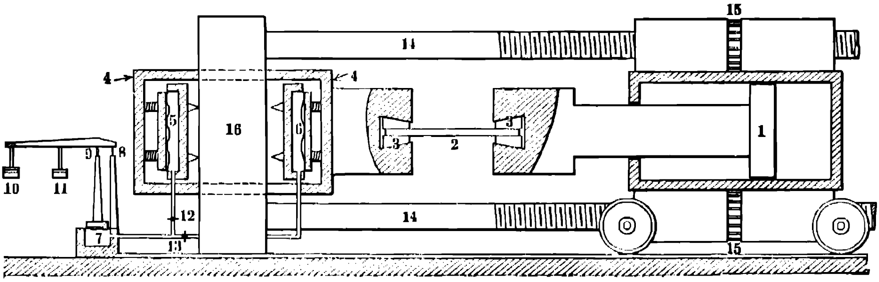

Fig. 4.—A Schematic Drawing Showing a Side Elevation of an Emery Testing Machine.

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* When the first machine was tested, a steel bar 5 in. in diameter was first broken under a load of 722,800 lb., and then a single horse-hair was tested, and the machine gave the strength (16 oz.) of this as accurately as a small spring-balance which was used for a check. *Rep. U. S. Test Board*, Vol. 2, p. 1.

and (9). In an actual machine there are several levers intermediate between the chamber lever and the scalebeam, but for simplicity only one lever is here shown. The hydraulic chamber and levers are inclosed in a glass case to prevent injury. Such confinement does not interfere with the operation of the scalebeam, since a device is employed by which imposition of the poise weights upon the spindles (10) and (11), can be made from outside of the case. The poise weights are generally gold plated to prevent corrosion. To accommodate specimens varying in length the straining head carrying the ram can be moved along the screws (14) by means of the power-driven nuts (15).

In making compression tests bearing blocks are placed over the jaws (3), and the hydraulic support (6) is brought to bear against the vertical beam (15); valve (12) is closed and valve (13) opened.

In calibrations, allowance is made for the bending forces in the plate fulcra and the ratio of the effective areas of hydraulic support and chamber. Since movement of fluid from the hydraulic support to chamber is negligible, friction is eliminated from the weighing system.

The largest Emery machine* is at the U. S. Bureau of Standards. This universal machine can test columns 33 ft. long to 2,300,000 lb.

The widely used Southwark-Emery testing machine utilizes the Emery support but substitutes an accurate pressure gage for levers and weights in measuring the load. A ground hydraulic ram operated by a multiple-rotating-cylinder pump imposes the load. The largest at the University of California has a capacity of 4,000,000 lb. and can test columns 33 ft. long.

COMPRESSION TESTING MACHINES

48. A Field for the Hydraulic Press.—To ascertain the compressive strengths of materials like concrete, stone, brick, and tile, a machine of great precision is not required. For work of this character an hydraulic press provided with an accurate gage for registering the fluid pressure in the ram has been found satisfactory.

The chief sources of inaccuracy in the hydraulic press are the variability of the friction between the piston and cylinder and at the stuffing box. In a well-designed press, however, these variations will be very small and may be neglected in rough work; or an average correction for friction may be made by calibrating the press with the packing tight and loose. A great variety of testing machines of this type are in use in this country; two will be briefly described.

49. A Machine for Testing in the Field.—A suitable press for either field or laboratory tests of 8 by 16-in. concrete cylinders or small stone cubes is shown in Fig. 5. This machine is built in capacities of 100,000 and 200,000 lb The upper head is equipped with a spherical bearing. Quick adjustment of the upper head may be obtained by the upper hand wheel, and specimens of concrete can be broken under uniform speed by a single turn of the one-stroke pump at the right. The lighter machine weighs 1600, the heavier 2000 lb.

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* For further information regarding this Emery Machine the reader is referred to *American Machinist*, Jan. 2, 1913, p. 1; Jan. 9, 1913, p. 50.

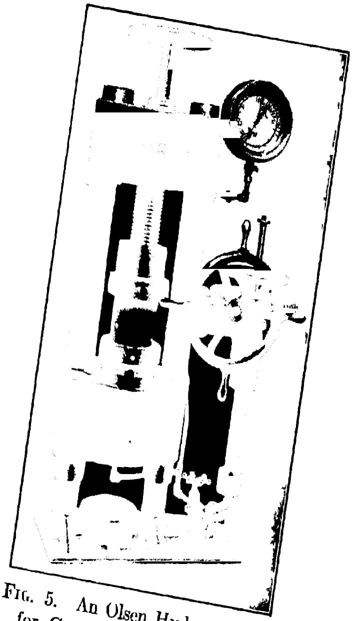
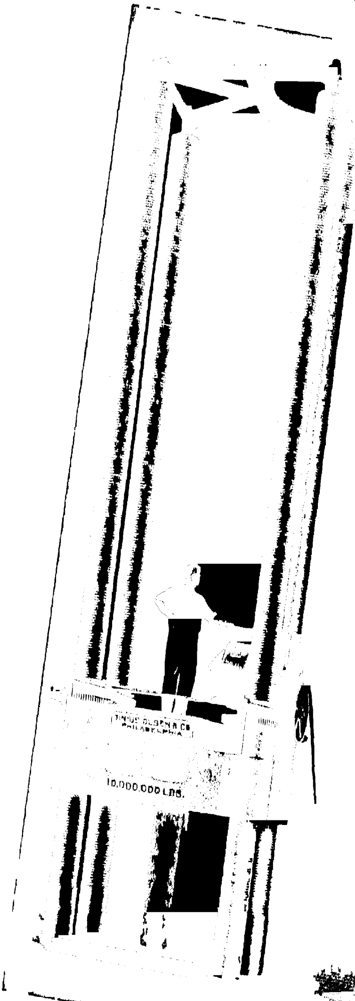


FIG. 5. An Olsen Hydraulic Press for Crushing Tests of Concrete or Stone



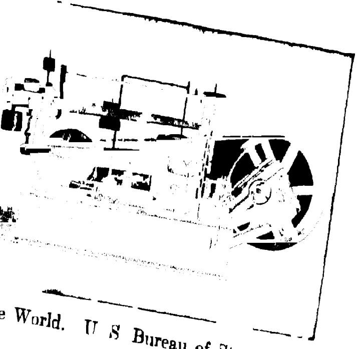


FIG 6—The Largest Testing Machine in the World. U S Bureau of Standards.

50. The World's Largest Testing Machine.—In Fig. 6 is shown the 10,000,000-lb. compression machine built by Tinius Olsen & Co, for the Pittsburg Laboratory of the U. S. Bureau of Standards. This machine in its present condition can be used to test specimens less than 25 ft. long and 4 by 4 ft. square within the capacity of the machine. The four screws are each $13\frac{1}{2}$ in. in diameter. Connected to the screws by long power-driven nuts is the adjustable upper head, weighing 30 tons. The spherical-seated lower head of the same weight is mounted upon the end of the ram of a huge hydraulic press, not shown in the illustration. To obviate uncertainty regarding frictional forces, the packing employed in this ram is so designed that these forces will vary directly with the pressure, a condition for which due allowance is made in the calibration. The intensity of the fluid pressure in the ram is transferred to a smaller hydraulic chamber which is sealed with a diaphragm and supported on the pump well. The pressure on the diaphragm is balanced through the lever system and screw-driven poise. The scale-beam is graduated to read loads on the specimen up to 2,000,000 lb. directly, and with end weights up to the capacity of the machine. Fluid pressure is supplied to the ram by means of a triple-plunger variable-stroke pump driven by a 15-h.p. variable-speed motor. This combination makes possible a considerable range in the speed of the lower head of the testing machine when desired. An air reservoir inserted in the supply line leading from the pump to the ram reduces the effects of the pulsations of the pump.*

TRANSVERSE TESTING MACHINES

51. General Remarks on Transverse Testing Machines.—On account of the large amount of testing done upon beams, it is often convenient to have machines especially adapted for transverse testing.

The main conditions, other than those previously mentioned in Art. 44, which should be fulfilled by a transverse testing machine are:

1. The parts of the machine should be sufficiently rigid so that the tops of the knife-edges supporting the beam and the bottom of the loading knife-edge will remain perpendicular to the sides of the beam throughout the test.

2. The supporting and loading knife-edges should, if necessary, bear upon auxiliary plates to prevent indentation. Also, these knife-edges should be so arranged that longitudinal tension in the specimen due to their rigidity is obviated. (See Art. 74.)

3. The machine should be equipped with a variety of slow speeds by which loads may be uniformly applied to the specimen at a rate which will permit the necessary observations to be made.

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* This machine is described in the *Eng. Record*, Sept. 28, 1912, p. 353.

52. Descriptions of Various Transverse Testing Machines.—Fig. 7 shows a 100,000-lb. Riehlé hydraulic transverse testing machine. By means of the valve operated by the hand wheel at the center of the machine fluid from the pump can be forced into either end of the double-acting ram, which moves the loading knife-edge. The support at the left end and the weighing apparatus at the right may be adjusted to spans varying from 4 to 20 ft. To save space this machine should be installed with the tops of the I-beams flush with the floor.

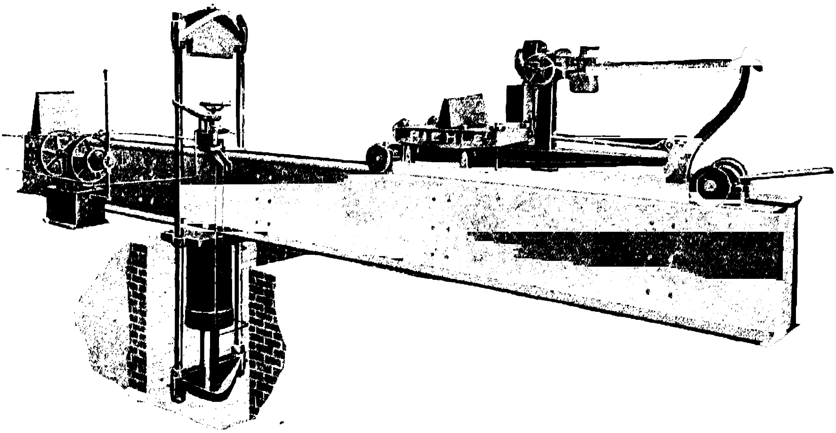

Fig. 7.—A 100,000-lb. Hydraulic Beam-testing Machine.

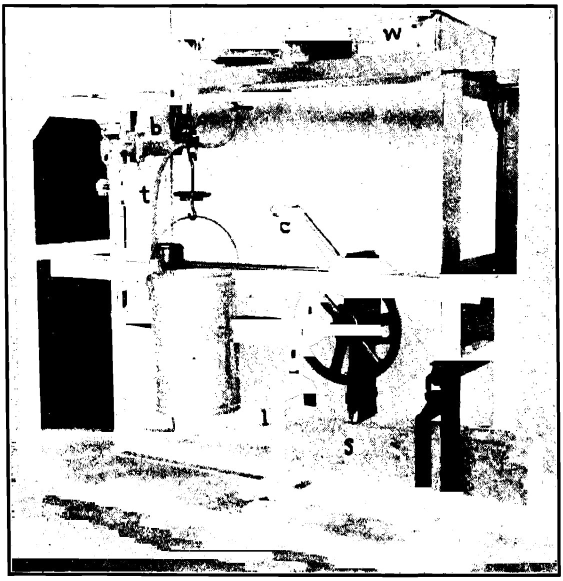

Fig. 8.—Concrete Beam Testing Machine. Designed and Used by Iowa State Highway Commission.

Figure 8 shows a machine for field testing a 6 by 6 in. concrete beam over an 18-in. span. To facilitate in maintaining the proper span length while the specimen is being placed in the machine, spacer bars, shown disengaged below the specimen (*s*), are provided. The load is applied by the crank (*c*) at a rate which keeps the scale beam (*b*) balanced. Rate of loading is in turn governed by the rate of flow of water from the tank (*w*) through the tube (*t*). Stirrup supports (*l*) eliminate end restraint and torsion in the specimen (*s*). Breaking of the beam cuts off the flow of water automatically. The load can be weighed to 5 lb. Two tests may be made per specimen.

Another form of transverse testing machine, much used in foundry work, is that shown in Fig. 9. In this machine the deflection is indicated on the graduated arc by means of an ingenious lever system not shown in the figure. The capacity is 5000 lb., and the span 1 ft.

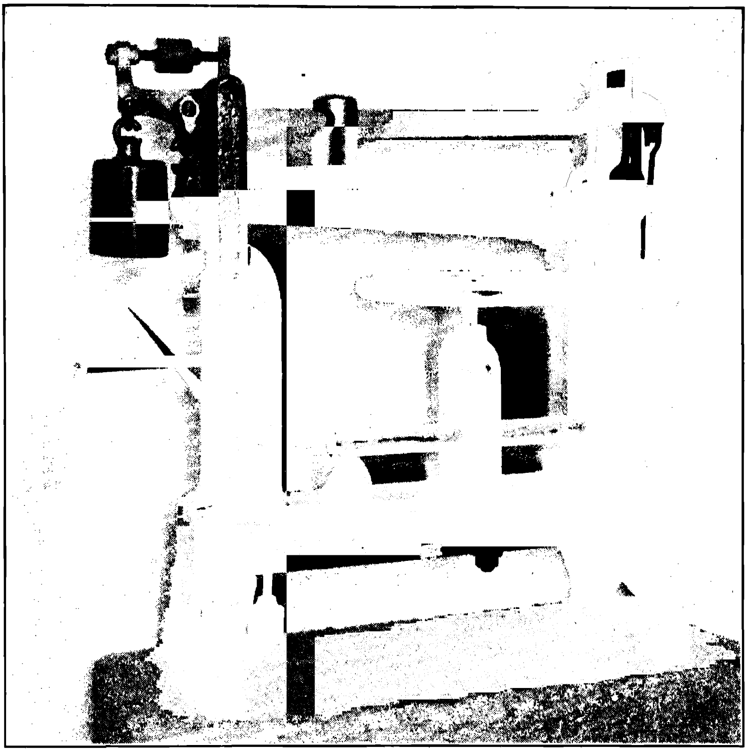

Fig. 9.—Cross-bending Testing Machine for Cast Iron. Deflection correctly measured.

Fig. 10 shows a transverse testing machine which records the load-deflection curve upon a specially ruled diagram. Imposition of the load is made through the hand wheel at the top. The load on the specimen actuates a system of levers which move the heavy pendulum along the graduated arc, shown beneath the frame. This motion produces a rotation of the drum. Through a follow pin placed at the center of the span directly under the specimen, a record of the deflection is gotten, The movement of this pin multiplied twenty times is transmitted to the pencil which moves vertically. Thus abscissas on the diagram measure loads and ordinates deflections. The machine is built for 12- or 24-in. spans. The capacity is 5000 lb.

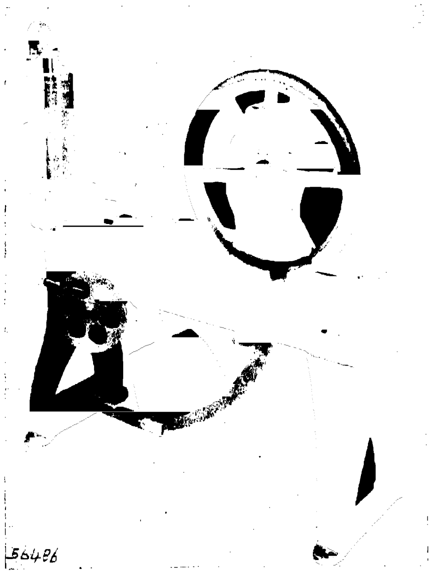

Fig. 10.—Olsen's Autographic Cross-bending Machine.

Cold-bend Testing Machines

53. Methods of Making the Test.—Up to this time, only machines in which the bending is accomplished by static pressure have been especially made for cold-bend tests. The power hammer is ordinarily employed when bending is accomplished by blows. The latter method is subject to much wider variations than the pressure method, but properly made is a more severe test than the former.

54. A Cold-bend Attachment.—The bending attachment shown in Fig. 11, designed by C. H. Scholer, can be inserted in a universal testing machine. The upper tool which is clamped in the movable head of the machine carries the pin around which the bar is bent. The bar rests on two cast-iron segmental rollers of 6-in. radius mounted on 2-in. hardened steel pins. The pins are supported in a frame consisting of two 4- by 6- by $\frac{3}{4}$-in. steel angles. The top of the angle frame is graduated to aid in setting the near bearing, in order to accommodate changes in thickness of specimen and pin. The device operates under low loads without imposing longitudinal forces due to roller friction, and can be used on specimens of short length.

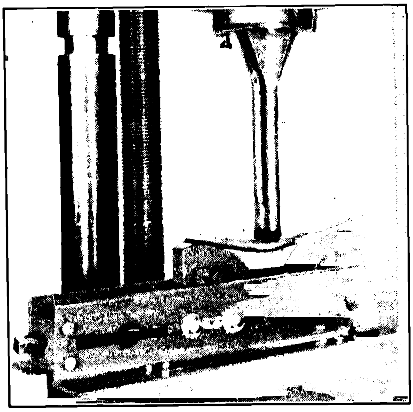

Fig. 11.—Scholer's Bending Attachment. (Courtesy of Baldwin-Southwark Corporation.)

55. Olsen's Cold-bending Testing Machine.—Fig. 12 represents a motor-driven cold-bend testing machine which will bend rods up to 2 in. in diameter or plates less than 6 in. wide. The specimen is held firmly by a wedge behind the left end, an adjustable vertical center pin, and an adjustable vertical pin placed back of the right end. The latter pin bends the specimen. By means of graduations on the table of the machine any bend up to 180 deg. may be determined The wire grating prevents injury to the operator through a sudden break of the specimen, but permits the making of observations during testing.

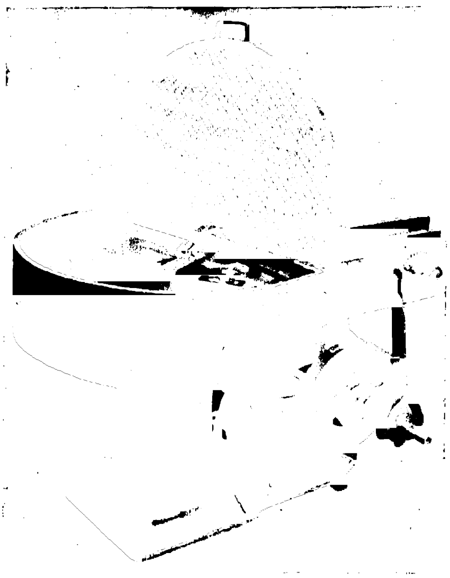

FIG. 12.—Olsen's Improved Cold-bending Machine.

SHEAR AND TORSION TESTING MACHINES

56. Transverse Shear Test Appliances.—Although it is impossible to produce in a body a transverse shearing stress unaccompanied by tension or compression, yet, on account of the frequent occurrence of shearing stresses in members subjected to cross-bending—in rivets, bolts, pins, etc.—and on account of the weakness of timber in shearing along the grain, it is often desirable to obtain an approximate knowledge of the shearing strength of a material. Several devices have been employed for this purpose; two will be briefly described.

In Fig. 13 is shown a double shear apparatus designed to determine the shearing strength of metals. With this appliance the end and central portions of the specimen are tightly gripped by hardened steel bearing plates which minimize bending distortion. However, on account of the small clearance between the central and end portions of the device, some frictional resistance is developed in testing. A comparison of the results of shearing tests on this apparatus with values gotten from torsion tests of very thin cylinders of like material indicates that the shearing device gives about 10 per cent higher unit stresses. The bars used in these tests were uniform in size. Grooving the bars in the planes of shearing would undoubtedly have lessened the error.

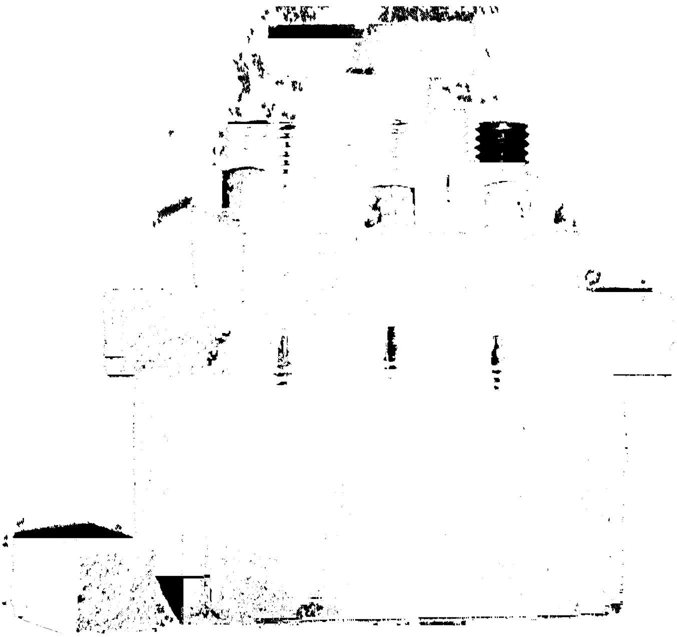

FIG. 13.—Johnson's Shear Tool.

A simple and satisfactory apparatus for making shearing tests on timber is shown in Fig. 14.

57. Torsion Testing Machines.—Shafting, wire, and elements of machines which are to be subjected to twisting are often tested in torsion to determine their torsional strength and shearing modulus of elasticity. Fig. 15 shows an Olsen 230,000-in.-lb. torsion testing machine. This machine will take shafting up to $2\frac{1}{2}$ in. in diameter and 22 ft. long. The motor operating through a chain drive and train of gears rotates a large gear carrying the chuck into which the right end of the specimen is securely fastened. The left end of the shaft is gripped by a similar chuck and transmits the twist to the lever system in the weighing head. To allow for longitudinal deformation of the specimen under test, the main lever of the weighing system is mounted on rollers, thus permitting considerable horizontal motion of the chuck. The lever shown at the left is employed to adjust the position of the weighing head on the rails.

Torsional testing machines of the pendulum type equipped with an autographic device for plotting torque-twist diagrams are also available. A 10,000-in. lb machine of this kind will be found especially suitable for

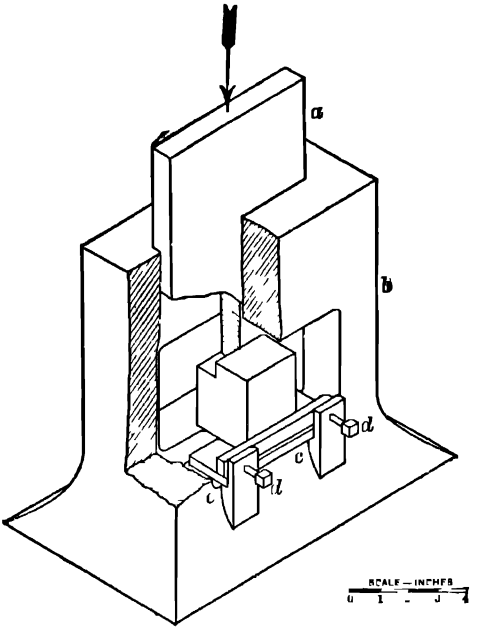

Fig. 14.—Forest Products Laboratory Shear Tool. Specimen is cut with a projecting shoulder.

demonstration purposes and for determining strength and maximum twist of small specimens. Values of the shear modulus and proportional limit cannot be determined with sufficient accuracy for acceptance tests.

The machine shown in Fig. 16 is adapted to test wires up to $\frac{3}{8}$ in. in diameter and over gage lengths of 8 in. or less. Its capacity is 500 in. lb. Tensile loads may be applied through weights shown at the left. The applied torque is automatically registered on the dial and the angle of twist can also be read from the rotating head.

Impact Testing Machines

58. Essential Conditions for Impact Testing Machines.—Since impact tests are made upon

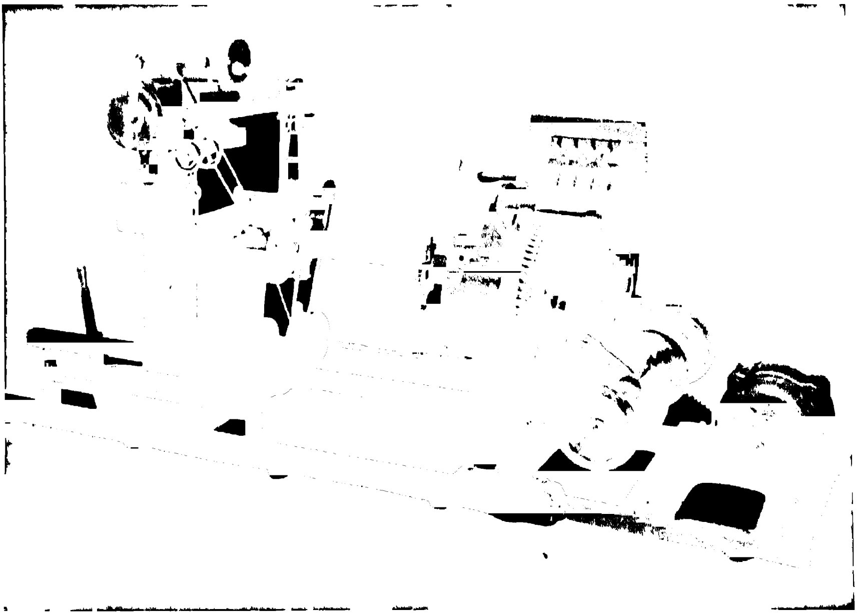

Fig. 15.—Olsen's Improved Torsion Testing Machine.

car wheels, car-couplers, car-axles, rails and rail joints to determine the resistance of such structural forms to shock, it is very necessary that the machine in which the tests are made shall be so constructed that the energy absorbed by the specimen can be determined. Inasmuch as the effect of a blow on the specimen depends upon the resistance of the specimen as well as the energy and mass of the falling body, it follows that a standard impact test involves a standard anvil resting upon a standard foundation, a standard hammer or tup, and a standard fall. Furthermore, in drop machines the axes of the tup, guides, anvil and specimen must be collinear; and the faces of the specimen, anvil, and tup must be parallel. On account of the impossibility of providing either an absolutely rigid anvil or tup, true quantitative results cannot be gotten. However, qualitative results of great value may be gotten from standardized tests. In practically all impact testing machines a transverse blow is delivered to the specimen either by a pendulum revolving about a horizontal axis or by a falling weight.

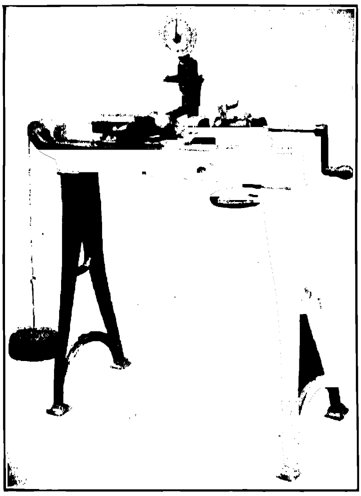

FIG. 16.—An Olsen Wire Tester.

59. Pendulum Impact Testing Machines.—The most used type of pendulum impact machine is the 217-ft. lb. Charpy shown in Fig. 17. The machine may be used for testing small simple beams which are supported by the outstanding arms and struck horizontally at mid-span by the hammer at the center of the pendulum. Beams of ductile materials must be notched across the side opposite the hammer if rupture is desired. The total angle through which such specimens may be bent by this machine is about 160 deg. The maximum striking

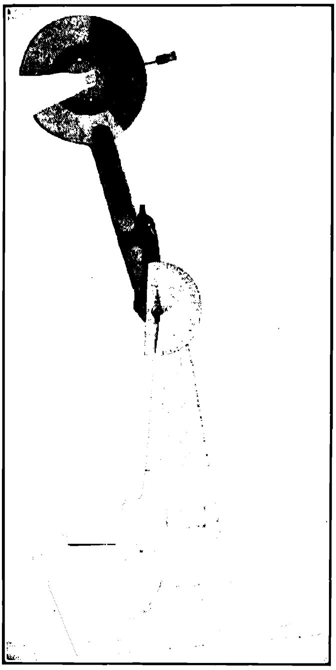

FIG. 17.—Charpy Impact Testing Machine.

velocity is 18 ft. per sec. The machine illustrated is also equipped to test small metal specimens in tension. The machine should be provided with a heavy base, and it is preferable that the latter should be securely fastened to a concrete floor or pedestal.

The potential energy of the pendulum is a linear function of the versine of the angle through which it is raised from the lowest position. Hence by reading on the graduated dial the initial angle to which the pendulum is raised and noting the angle to which it rises after breaking the specimen, it is possible to calculate both the initial and residual energy of the pendulum. The difference between these energies closely approximates the energy consumed by the specimen. In a given set of tests it is desirable to use the same initial angle both to save unnecessary computations and to maintain the striking velocity of the pendulum constant. In tests of fragile specimens, calibration should be made to determine the energy losses due to friction at bearings and air resistance.

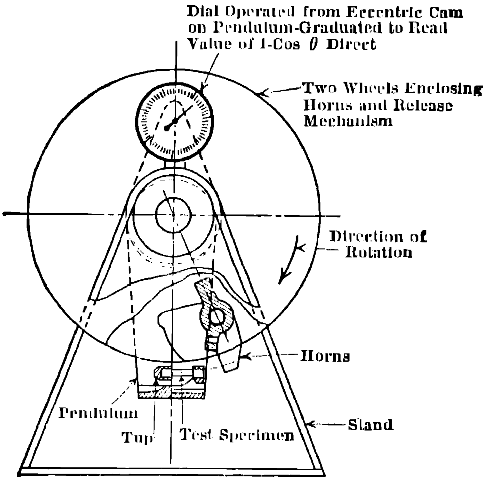
Dial Operated from Eccentric Cam on Pendulum-Graduated to Read Value of 1-Cos θ Direct
Two Wheels Enclosing Horns and Release Mechanism
Direction of Rotation
Horns
Stand
Pendulum
Tup
Test Specimen

FIG. 18.—Principle of Mann-Haskell High-Velocity Tension-Impact Testing Machine.
(*Proc. A.S.T.M.*, Vol. 36, Pt. 2, p. 85.)

With the ordinary type of pendulum impact machines the velocity of tup is low. A high velocity tension impact testing machine has recently been invented by Haskell and Mann of the Ordnance Department of the U. S. Army.* Figure 18 shows the principle of operation of this machine. The two rotating wheels carry a pair of horns and balancing counterweight, both of which can be released when the wheel speed has attained the desired value. The horns then engage the tup attached to the left end of the test specimen. The right end of the specimen is fastened to the pendulum, which hangs vertical until the tup is thus struck. The upward swing of the pendulum is indicated on the dial, which provides a means of calculating with reasonable accuracy the energy conserved in rupturing the specimen. Riehlé Testing Machine Division of American Machine and Metals, Inc., now manufacture this machine, capable of producing a maximum velocity of 250 ft. per sec. In testing with this machine Mann used a specimen 3 in. long provided with threaded ends having an outside diameter of $\frac{3}{4}$ in. and a gage length 1 in. long with a diameter of 0.252 in. The relation of diameters of end and gage portions is such that the work of deformation is restricted almost entirely to the reduced portion of this specimen.

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* See *Proc. Am. Soc. for Testing Matls.*, Vol. 36, Pt. 2, p. 85.

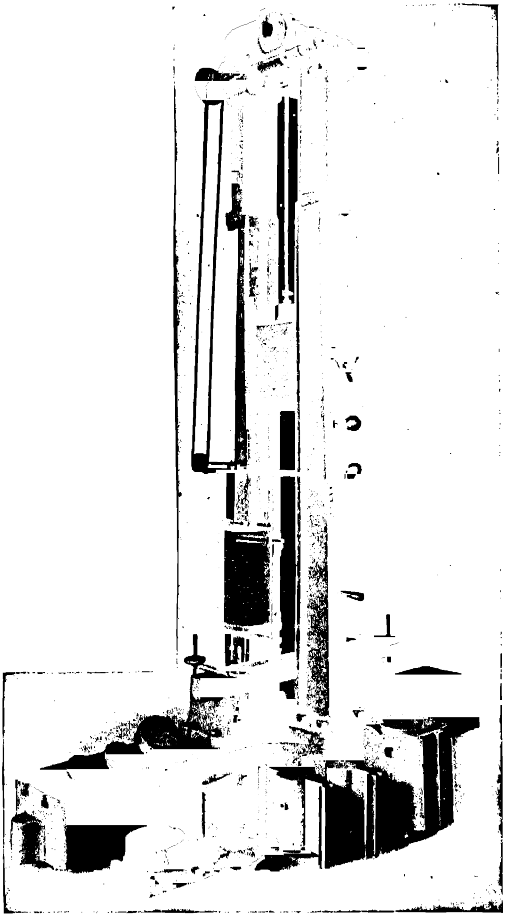


Fig. 19.—A Turner Impact Testing Machine.

60. Drop Impact Testing Machines.—Figure 19 illustrates a Turner impact testing machine for either compression or transverse impact tests. In this machine the tup is hoisted by an electric motor placed at the top. Release of the tup is secured by reversing the current through the suspending magnet. A pencil moving over paper fastened to the revolving drum, shown just above the specimen, records the behavior of the specimen. Two sizes of this machine are made, the larger having a capacity for beams 8 ft. long and 12 in. wide; the maximum drop attainable is 6 ft., and the weights of tup range from 50 to 500 lb. With

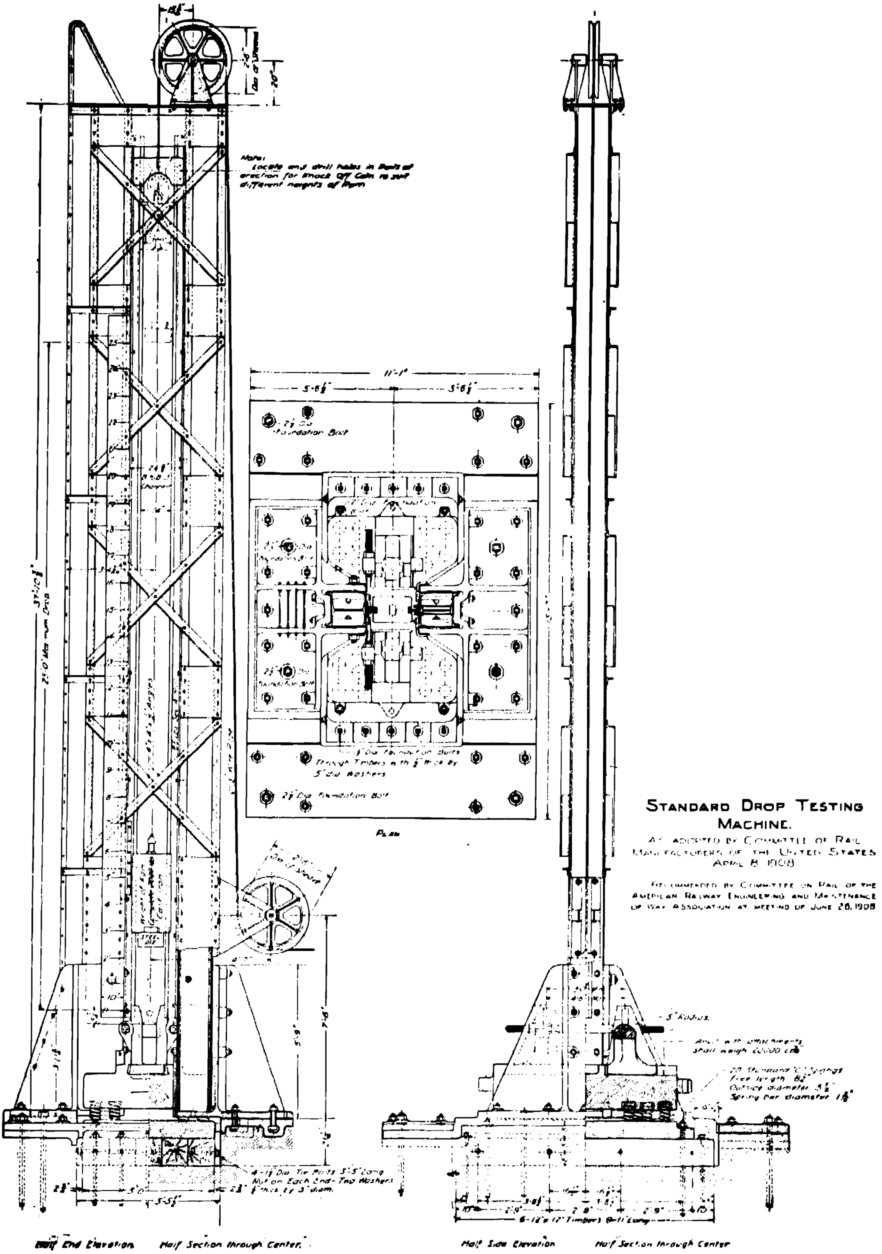

Note:
Locate and drill holes in Posts at erection for Knock Off Cam to suit different heights of Drop
11'-1"
5'-6½"
5'-6½"
2¼" Dia Foundation Bolt
Plan
37'-10⅛"
25'-0" Maximum Drop
24½" 3 B. Channel
5'-9"
7'-8"
4-1⅛" Dia Tie Bolts 5'-5" Long Nut on Each End - Two Washers ⅝" thick by 3" diam.
2⅝"
5'-0"
5'-5½"
2⅝"
5" Radius
Anvil with attachments shall weigh 20000 Lbs
20 Standard "C" Springs Free length 8¾" Outside diameter 5¼" Spring bar diameter 1⅛"
6-12"x 12" Timbers 8'-11" Long
STANDARD DROP TESTING MACHINE.
As adopted by Committee of Rail Manufacturers of the United States April 8 1908
Recommended by Committee on Rail of the American Railway Engineering and Maintenance of Way Association at meeting of June 26, 1908
Half End Elevation
Half Section through Center.
Half Side Elevation
Half Section through Center

FIG. 20.—Standard Drop Testing Machine for Rails.

this type of machine tests can be made to ascertain the elastic properties in addition to the energy of rupture of a specimen.

In Fig. 20 is presented a drawing of the standard drop testing machine adopted by the American Railway Engineering Association for making tests on rails. A noteworthy fact about this machine is the method of supporting the anvil. The latter weighs 20,000 lb., and is supported on 20 M.C.B.A. Standard "C" springs arranged in groups of five at each corner of the anvil. No connection exists between the vertical guides and the anvil. For further information relating to this machine see *The Manual* of the A.R.E.A.

APPARATUS FOR DETERMINING HARDNESS

61. The Sclerometer.—In 1886 Turner developed his sclerometer to measure hardness by ascertaining the weight required to cause a diamond to make a visible scratch. Martens modified this test by measuring the weight required to produce a scratch 0.01 mm. wide with a conical diamond point. Such tests have attracted attention in this country. See Report of Committee E-4 of A.S.T.M. in 1926.

62. Ball Indentation Tests—Brinell and Rockwell.—The penetration of a steel ball or diamond point into a finished surface is the most used method for testing the hardness of metals.

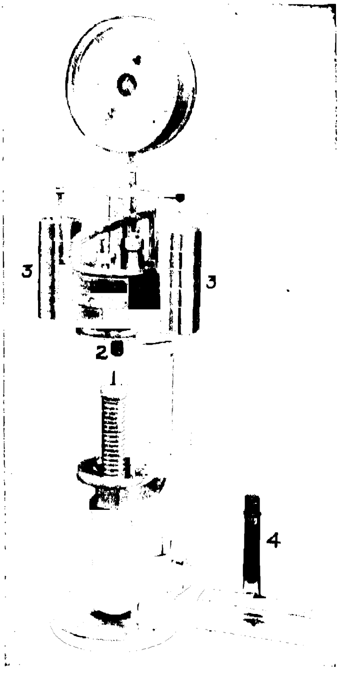
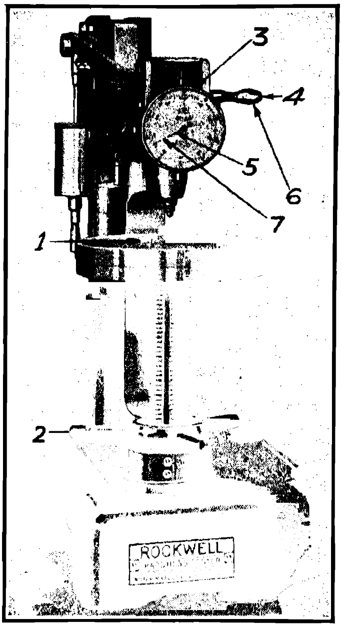


FIG. 21.—Olsen's Apparatus for Making the Brinell Hardness Test.

In testing with the Brinell machine shown in Fig. 21, the specimen, resting on the anvil (1), is raised until it touches the 10 mm. hardened steel ball (2). The ball is attached to the piston of an oil ram. Pressure, usually 3000 kg., is applied to the specimen by operating the pump handle until the accumulator weights (3) are lifted. The ratio of the load in kilograms to the surface area of the indentation in square millimeters forms the basis for the Brinell hardness scale. A specially .constructed microscope (4) is ordinarily used to measure the diameter of the indentation. Devries of the U. S. Bureau of Standards found that the indentation can be more accurately determined by measuring the difference in depth of indentation due to a light load applied before and after the test load. He also found that a linear relation exists between load and depth of indentation for pressures less than 3000 kg. Portable Brinell devices are also available.

For the Rockwell hardness tester, Fig. 22, two hardness scales are provided—the B-scale in which the depth of indentation of a $\frac{1}{16}$-in. steel ball under an increase in load of 100 kg. is the basis; and the C-scale in which the penetration of a 120-deg. conical diamond point (called a Brale) under a 150-kg. increase in load is the basis. For very soft metals larger balls and lighter loads may be employed. Registration of penetration is made on a dial reading to 0.002 mm. The scale reading of the dial is arranged to increase with the hardness of the specimen.

In testing with the Rockwell machine the work is placed on the anvil (1) and forced upward against the penetrator by turning the hand wheel (2) until a 10-kg. initial load has been applied. The dial (3) is then set to read zero and the handle (4) pushed backward to release the major load 100, or 150 kg., which is superimposed at a given rate of speed by the dash pot. After the dial pointer (5) has come to rest the handle is pulled forward (6) releasing the major load but leaving the minor load imposed. The Rockwell hardness number (7) is then automatically registered by the dial pointer.



(Courtesy Wilson-Maculen Co.)

FIG. 22.—How to Operate the Rockwell Hardness Tester.

63. The Shore Scleroscope.*—In this apparatus the specimen is struck by a small diamond-pointed hammer falling freely. The rebound of the hammer is measured and gives an indication, according to its inventor, of the resistance to indentation or hardness. Figure 23 shows a recording type of scleroscope. In this device the tube is made vertical by adjusting the screws at the base of the instrument until the plumb rod, exposed at the front of the tube, is centered. The diamond-pointed hammer is elevated in the tube and released by turning the knurled knob near the bottom of the tube. The rebound of the hammer is recorded by the dial hand which remains fixed until the knurled knob is again turned for another test. In the older type of scleroscope the hammer is allowed to fall in an accurately ground glass tube from a height of about 10 in. and the rebound is noted by the eye. Since slight differences in the sharpness of hammer points greatly affect the rebound, the hammer must be frequently tested on a standard surface. The surface ordinarily used is of hardened steel which gives a rebound of 100 on the scale.

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* Manufactured by Shore Instrument and Mfg. Co., Jamaica, N. Y.

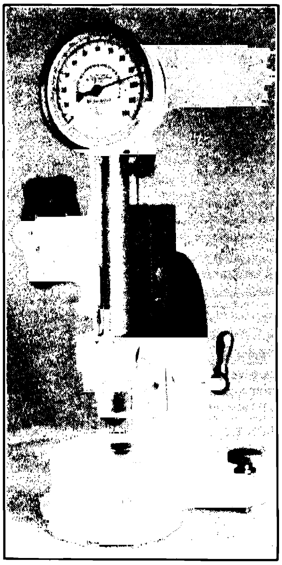

Fig. 23.—Shore Scleroscope.

Endurance Testing Machines

64. Wöhler's Repeated-stress Testing Machines.—Owing to value and importance of the systematic studies of Wöhler upon the fatigue of metals, his appliances have received considerable attention. Fig. 24 shows his apparatus for repeated tensile stresses. Here the specimen (*A*) is stressed through the lever (*L*) and spring (*s*) acting on the auxiliary lever (*m*). The pull of the spring (*s*) is measured by the starting of the adjusted calibrated spring (*s'*) through the terminal lever (*g*). The nut at the od (*d*) is adjusted to give the minimum load on the spring (*s*) by starting the spring (*s'*) when adjusted to a particular tension, and the cam movement of (*d*) to its extreme downward position is made to give the requisite maximum stress in the specimen by adjusting the spring (*s'*) so as to just lift at this position of (*d*). The rod is adjustable by means of a turnbuckle. In this way the bar (*A*) can be stressed

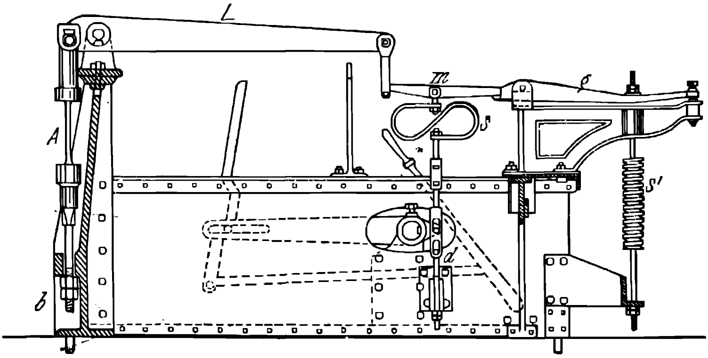

Fig. 24.—Wöhler's Machine for Repetitions of Tensile Stress.

in tension between any chosen limits. Wöhler also designed special devices for repeating bending stresses and for repeating torsional stresses.*

65. Reversed Bending Endurance Testing Machines.—Fig. 25(*a*) shows a type of rotating beam machine which has been extensively used both in the United States and in England. The machine shown is one which was used at the University of Illinois. The specimen, *A*, rests in ball bearings at *B* and *E*. The load is applied by means of two symmetrically placed ball bearings at *C* and *D*. This loading produces uniform bending moment between *C* and *D*. The revolutions counter is at *N*, and the machine has an automatic device (not shown) which stops the machine when the specimen breaks.

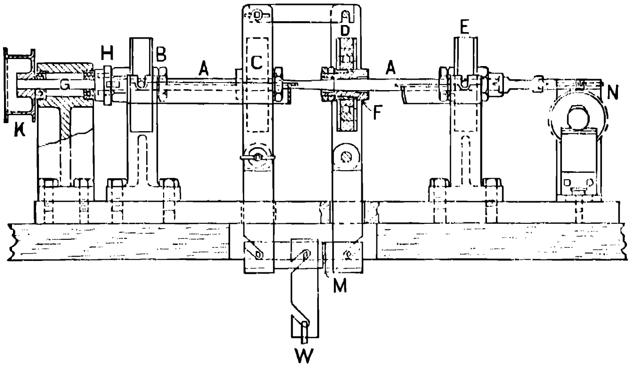

Fig. 25 (*a*).

Fig. 25(*b*) shows another reversed bending machine which was developed at the University of Illinois. In this machine the cantilever specimen, *N*, is not rotating, but is held fixed at one end in the grips, *V*. The load is applied at the other end of the specimen by means of a ball bearing, *B*, and

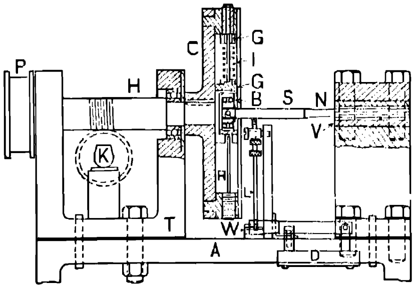

Fig. 25 (*b*).

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* See *Engineering*, Vol. 11, p. 199, 221, 224, etc.

a calibrated spring, *I*. As the rotating head, *C*, revolves, the free end of the specimen is forced to travel in a circle about the axis of the gripped end, with the result that the specimen is subjected to reversed bending stress. This type of machine was first developed so that a thermocouple could be applied to the specimen, in determining the endurance limit by the " rise-of-temperature " method. (See Art. 831.)

66. Axial Stress Endurance Testing Machines.—Fig. 26(*a*) and Fig. 26(*b*) show two machines developed at the University of Illinois for determining the endurance limit in axial tension-compression.

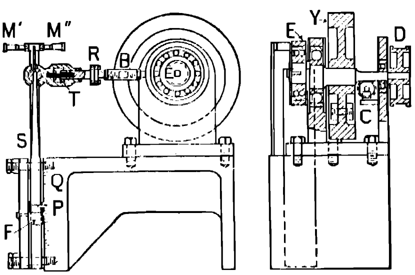

FIG. 26 (*a*).

In Fig. 26(*a*) the specimen, *T*, is forced to deflect the calibrated spring, *S*, by means of the eccentric, *E*, and the connecting rod, *R*. The ratio of tension to compression can be varied by means of the turnbuckle, *B*.

In Fig. 26(*b*) the specimen, *S*, has its outer end fastened rigidly to the rotating head, *H*. The lever, *L*, with a fulcrum at *N*, applies the load to the specimen through a ball bearing. The load, *W*, is applied to the free end of the lever as shown. For the position indicated the specimen is in axial compression, and when the rotating head has revolved 180 degrees the specimen is in axial tension.

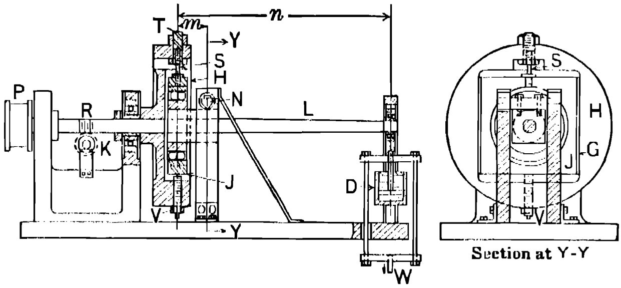

FIG. 26 (*b*).

AUXILIARY APPLIANCES EMPLOYED IN LOADING SPECIMENS

67. The Transmission of Load to a Specimen.—In making tests of materials it is very desirable that the experimenter have control not only of the magnitude but also of the places of application and the directions of the forces applied to the specimen. Unless such conditions obtain stresses of a different kind or of undesirable magnitude may be produced in the test-piece. In most tension and compression tests an axial load is sought; in most transverse tests a loading which produces bending in a given plane is desired. On account of the devices employed to transmit pressure from the testing machine to the specimen, a brief description of some of these appliances will not be given.

GRIPPING DEVICES FOR TENSION TESTS

68. Wedges or Grips.—By far the most frequently used device for holding tensile specimens in the jaws of the testing machine is a set of four serrated wedges. The flat wedges shown in Fig. 27 are for specimens of rectangular cross-section; the grooved wedges are used with cylindrical test-pieces.

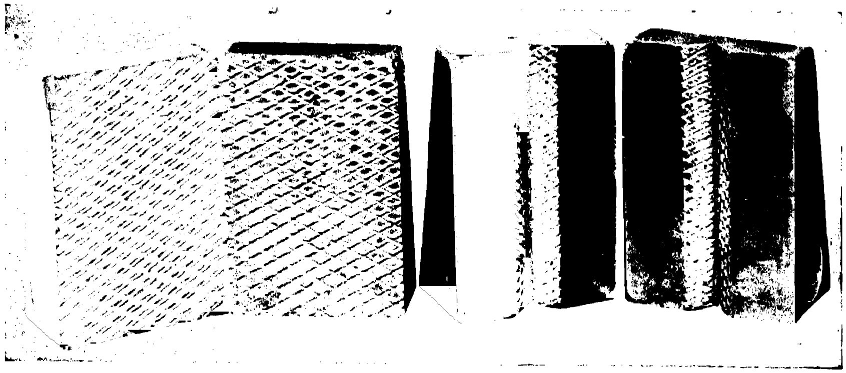

FIG. 27.—Flat and Grooved Wedges for Tensile Tests.

Liners are placed in back of the grips in testing thin specimens. Fig. 28*d* shows the proper method of gripping a test-piece when wedges are employed. To prevent sticking in the jaws of the machine the backs of the grips should be coated with a heavy lubricant.

Wedges are often objected to on the ground that they crush the specimen and pull unevenly on opposite sides of a test-piece, thus producing bending or oblique stresses. However, for rough commercial testing experience has proven such grips to be satisfactory.

69. Spherical Seated Holders.—In scientific testing to determine the elastic limit of a material, it is desirable to secure as close an approach to an axial loading as possible, and a method more refined than indicated above should be employed. For such tests spherical seated holders of the type shown in Figs. 29 and 30 have been much used.

The efficiency of this device is dependent both upon the skill of the mechanic in making the appliance and in fashioning the specimen, and upon the care exercised in using the device. To reduce the frictional resistance of the spherical seat to a minimum, the radius of the sphere should be made as small as a proper consideration of the crushing strength of the ball will permit, the ball and seat should be ground to fit, and the bearing should be lubricated with a thin film of oil. Even with a well-made holder and careful manipulation, extensometer measurements taken on opposite sides of a specimen will often differ considerably. This difficulty may be partly removed by applying a small load, reading the extensions, then removing the load and adjusting the specimen slightly to overcome the eccentricity.

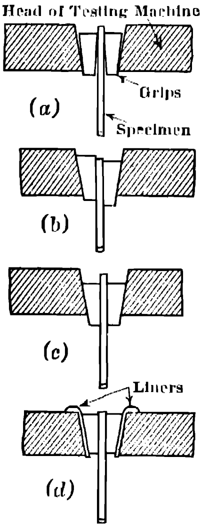

Fig. 28.—Correct (*d*) and Incorrect (*a*, *b*, *c*) Methods of Gripping Tensile Specimens with Wedges.

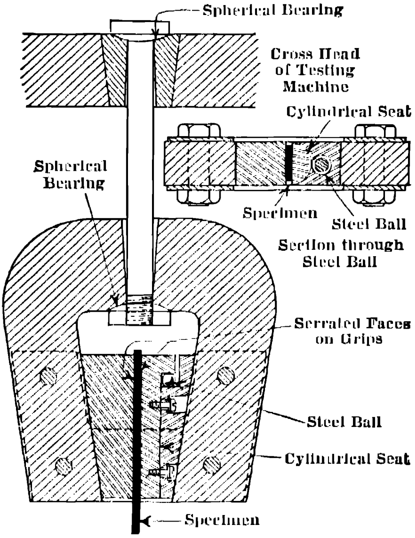

Fig. 29.—Gripping Device for Sheet Materials.

(See *A.S.T.M. Standards* for Tension Tests.)

A type of holder which is suitable for use with tempered steel specimens is shown in Fig. 30*b*. Portion *A* is a socket nut which is threaded to fit the lower end of the bolt *B*. The latter may be provided with a spherical head or threaded at the upper end to fit the holder of Fig. 30*a*. After the head of the test-piece has been inserted through the hole in portion *A*, the halves of the spherical-seated washer *C* are slipped about the specimens and held in place by a rubber band or a split ring. Parts *A* and *B* are screwed together, and then the lower end of the specimen is socketed.

70. Crossed Knife-edge Suspension.—Fig. 31 shows a form of crossed knife-edge suspension which has been successfully used at the Materials Testing Laboratory at the University of Wisconsin in making tension tests of concrete specimens.

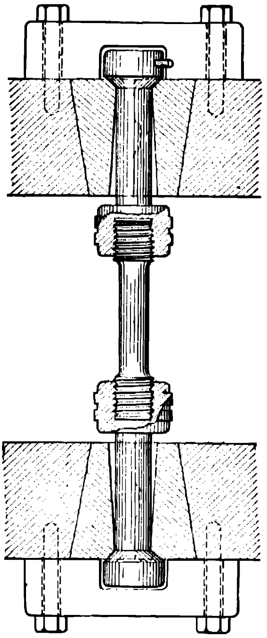

FIG. 30a.—Holders with Spherical Seats for Tensile Tests.

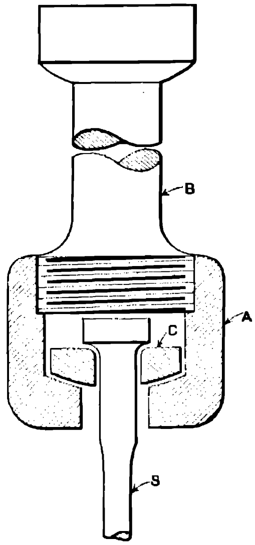

FIG. 30b.—Spherical-seated Sockets for Hard Steel Specimens. (After K. W. Zimmerscheid in *Trans. Soc. Auto. Engr.*, Vol. 8, pt. 2, p. 162.)

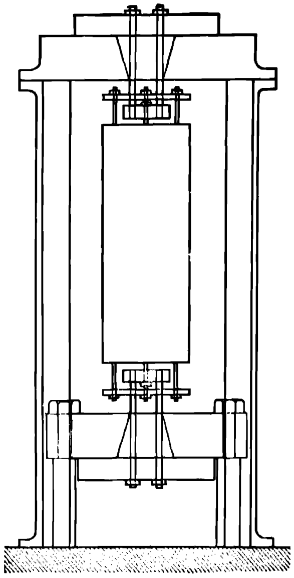

FIG. 31.—A Crossed Knife-edge Suspension for Testing Concrete Cylinder in Tension.

LOADING APPLIANCES FOR COMPRESSION TESTS

71. Rigid Bearing Blocks.—In rough testing compressive loads are applied through heavy blocks one of which is fastened to the lower side of the pulling head of the testing machine and the other is supported by the weighing table. With such bearing blocks it is very difficult to secure an axial load on the specimen.

72. Adjustable Bearing Blocks.—For carefully conducted tests various appliances have been devised for imposing compressive loads. The spherical bearing block, shown in Fig. 32, has been extensively used. Some experimenters prefer to support this device on the weighing table beneath the specimen, others hang it from the moving head above the specimen. The latter position is the simpler for operation.

Ball-bearing blocks have also been widely used in compression tests. Fig. 33 shows a form of block which is satisfactory for such tests.

In using any of the above devices great care must be exercised to make the axes of the bearing block, specimen, and testing machine collinear. If deformation measurements are being taken the load on the specimen may be made axial in the following manner:

Readings of the shortening of elements on opposite sides of the specimen may be taken for moderate loads and the specimen adjusted on the bearing block until the deformations of all elements are equal.

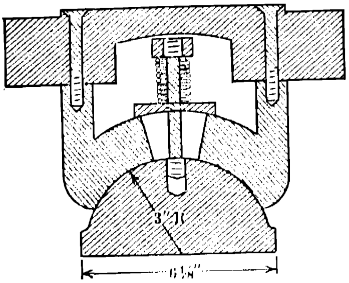

Fig. 32.—A Spherical Bearing Block used at the University of Wisconsin.

In testing columns for the purpose of checking existing theories, most investigators have attempted to make the ends of the specimen free to revolve. Professors Bauschinger, Considére,* Tetmajer, and Lilly mounted their columns on cone or knife-edge bearings at the gravity axes. The roller bearings designed at the Forest Products Laboratory, Fig. 34, have also proved satisfactory. These bearings have been loaded to

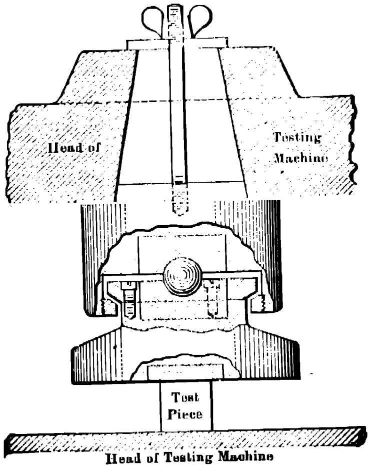

Fig. 33.—Ball-bearing Block for Compression Tests.

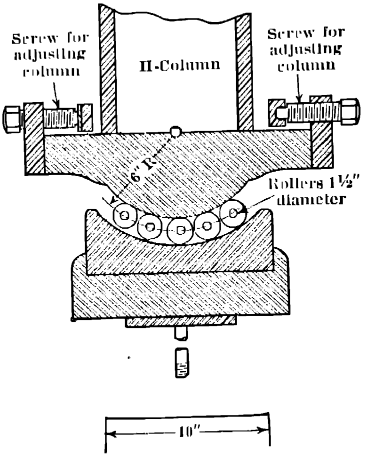

Fig. 34.—Forest Products Laboratory Roller Bearing Block.

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* Ingénieur-en-chef des Ponts et Chaussées, France; see *Report of the French Commission on Methods of Testing Engineering Materials*, 1895, Vol. 3, p. 124.

800,000 lb. When well greased, the coefficient of friction is about 0.025. The adjusting screws are convenient in centering the column as desired.

Supporting and Loading Devices for Transverse Tests

73. V-blocks.—Commonly the supporting tools for transverse tests are inverted V-blocks which are either fixed to the bed of the testing machine or which may be slid into the desired position. The edges of the blocks are rounded to produce line contact across the beam, and are surmounted by metal bearing plates when tests of non-metallic specimens are to be made. Through a similar V-block fixed in the jaws of the movable head of the testing machine and bearing upon a metal plate or saddle, the load is imposed upon the test-piece. Obviously, with the above arrangement the beam is subjected to more or less longitudinal restraint. Furthermore, if the lines of contact on the beam are not parallel to the edges of the V-blocks, the test-piece will be subjected to torsion.

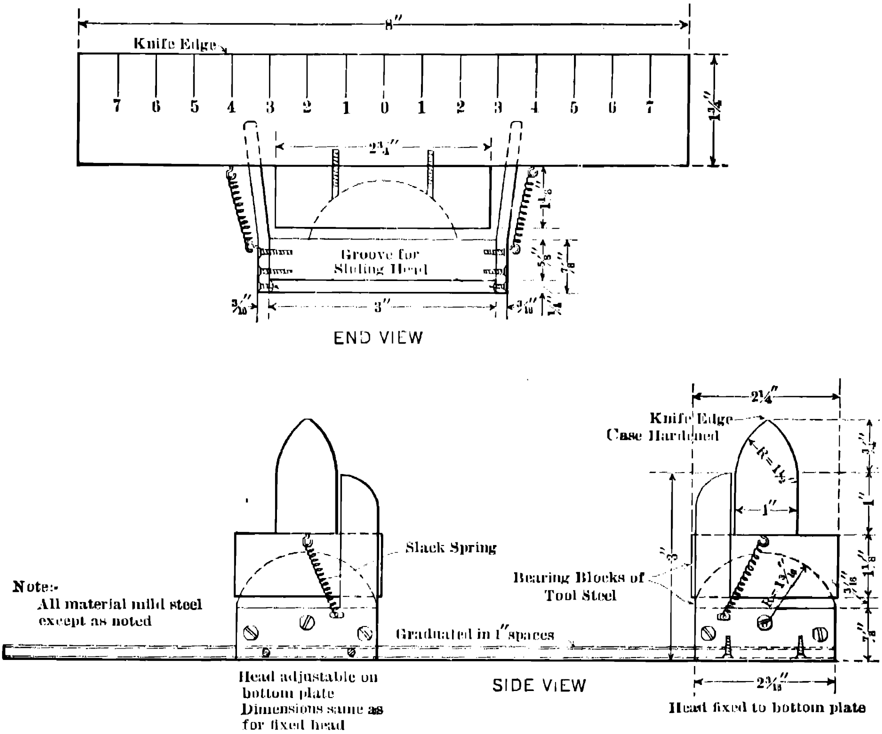

Fig. 35.—Knife Edges with Spherical Bearings for Cross-bending Tests on Brick.

74. Adjustable Bearing Blocks.—To avoid the errors encountered in the use of fixed V-blocks it has been customary to mount the beam on adjustable supports. A much-used form of support consists of a V-block mounted on a spherical seat. Fig. 35 shows such a device which has been employed considerably at the University of Wisconsin in testing small specimens. Fig. 36 illustrates the form of support which Tinius Olsen & Co. advocate for testing large beams.

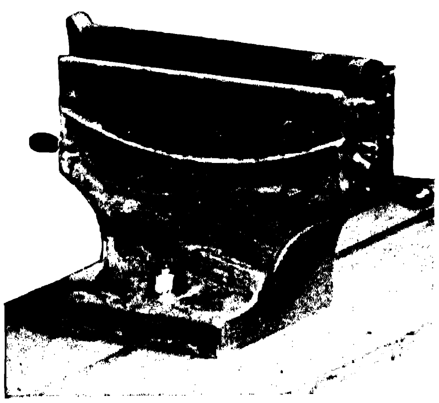

FIG. 36.—An Adjustable Supporting Block Used in Testing Large Beams.

In careful work it is advisable to transmit the load from the pulling head to the specimen, or to the auxiliary beams used in loading, through a spherical bearing block. If the specimen is loaded at more than one point, rollers resting on hard steel plates should be employed to apply the pressure of the auxiliary beams upon the test-piece.

BEDMENTS

75. The Use of Bedments.—Even though adjustable bearings be employed, it is necessary that the contact surfaces of the test-piece be plane and approximately parallel. Metal specimens should always be machined or ground until the above conditions are fulfilled. For the best results, specimens of stone, brick, or concrete should also be ground. However, on account of the length of time and the equipment required to grind specimens, many experimenters bed such test-pieces in some material which will lessen the effects of surface inequalities. If a bedment is used it should be made as thin as possible; also, it should be composed of a substance which will not spread or flow under pressure and which possesses the same strength and elastic properties as the specimen. The latter condition is difficult to satisfy and is, unfortunately, often disregarded.

76. Plaster of Paris.—Bedments of plaster of Paris have long been used. In making such bedments it is good practice to place a sheet of sized paper between the plaster of Paris paste and the specimen to prevent the absorption of water by the latter, since this action invariably affects the strength of the test-piece. The bedments should be made plane and perpendicular to the axis of the specimen after which a slight pressure should be brought to bear upon the soft bedment and allowed to remain until the plaster of Paris has set.

77. Cement Mortar.—Laboratory practice for molding and capping concrete and mortar compression specimens is given in (A.S.T.M. Standards C39-33.) Where bedment is necessary, however, plaster of Paris and neat cement pastes are often used. Such bedments must be made long enough before the time of testing to permit the paste or mortar to harden. The addition of 2 per cent of calcium chloride, by weight, to a high early strength portland cement paste gives a capping mortar with a compressive strength of 6,000 lb./in.^{2} at 1 day. (See also Art. 395.) In general, only the tops of the specimens need be treated, the procedure being as follows: The specimen is placed upon a leveled surface and a thin coat of plastic mortar applied to the top. The bedment is then finished by pressing down upon it a piece of plate glass and truing with a spirit level.

78. Miscellaneous Bedments.—Beaver Board, blotting paper, leather, millboard, and white pine board are occasionally used as bedments. Of the common sheet bedments, Beaver Board is most satisfactory; white pine board, millboard, and leather are of some benefit; while blotting paper, sheet lead, and rubber are detrimental. (H. F. Gonnerman, *Proc. A. S. T. M.*, 1924.)

APPLIANCES FOR MEASURING DEFORMATIONS

Extensometers

79. Essential Features of Extensometers.—For measuring the elastic extension of materials subjected to tensile loads, a great variety of devices have been employed. Four principal types of extensometers are micrometer-screw with electric-contact, indicating dial, multiplying lever, and mirror apparatus. In any type of extensometer the following conditions should obtain:

1. The apparatus should be directly attached to the test-piece.

2. It should be arranged to measure deformations on opposite sides of the specimen if the change in length of the axis is to be determined. If the maximum deformation of any element is desired, measurements along at least three elements, preferably 120 deg. apart, are required.

3. The portions of the apparatus transmitting deformations should be parallel to and equidistant from the axis of the specimen. If only two measurements are made these should be along lines in the plane of the axis and equidistant from it.

4. The apparatus should be so arranged that the relative positions of all parts with respect to the axis of the specimen will remain the same throughout the test.

5. For precise measurements the instrument should read to at least 0.0001 in. and should be sensitive to half that amount. To determine

the accuracy of the instrument, its readings should be checked by comparison with a standardized measuring device.

6. The apparatus should be so constructed that it may be quickly applied to or removed from a specimen without interfering with the application of the load.

80. A Micrometer-screw Electric-contact Extensometer.—In Fig. 37 is shown a simple form of micrometer-screw extensometer reading to 0.0001 in. The upper and lower portions of the apparatus form parts of an open electric circuit. Contact between a micrometer-screw and rod is announced by the bell which rings when the circuit is closed. Only a small constant current is used, since a large current will jump an appreciable gap between screw and rod. On account of the uncertainty of bell mechanisms telephone receivers are often substituted. To prevent a closed circuit through the specimen the vertical rods are insulated by gutta percha sleeves placed in the top collar of the instrument.

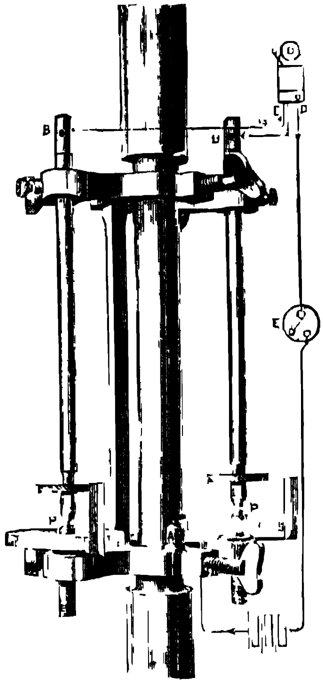

FIG. 37.—A Micrometer-screw Electric-contact Extensometer.

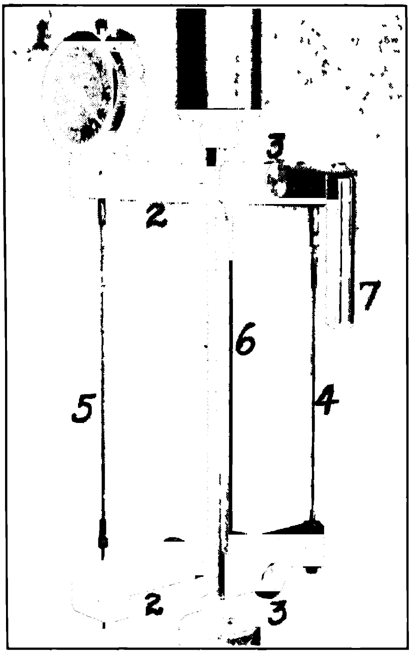

FIG. 38.—An Indicating Dial Extensometer.

This common type of extensometer is quite satisfactory for student work, and with skillful handling will give accurate results. In operating the screws on this instrument, however, great care must always be exercised to make the plane of the turning couple exerted by the fingers perpendicular to the axis of the screw.

A similar type of instrument carries a rod at the left attached to the lower frame and pivoted on the upper. The micrometer on the right then reads double the average extension.

81. An Indicating Dial Extensometer.—Indicating dials reading to 0.001 or 0.0001 in. have a very wide range of application in measuring deformations and deflections. Figure 38 shows an inexpensive extensometer in use at the University of Wisconsin. It is a modification of an earlier form devised by H. F. Moore. A 3-in. Federal dial (1) reading directly to 0.0001 in., equipped with adjustable scale and revolution counter, provides an easily read and accurate indicator. The upper and lower yokes (2) are of aluminum and pivot on the attachment screws (3). The vertical drill rods (4) and (5) connecting the yokes are provided with small ball and socket joints. Rod (4) acts as a pivot so that rod (5) transmits double the average elongation of the specimen (6) to the dial. The counterweight (7) serves to balance the weight of the dial.

In assembling the device a gage bar, not shown, clamps the yokes at the desired distance apart until the instrument has been attached to the specimen. Care must be taken to center the device so that the plane of the rods contains the specimen axis and each rod is equidistant from that axis.

If it is desirable to read strains on opposite sides of the specimen, pivot rod (4) may be replaced by a rod similar to (5) and a second dial inserted on the top frame. Wire-wound dials similar to these shown in Fig. 46 have been used with mountings similar to that shown in Fig. 38.

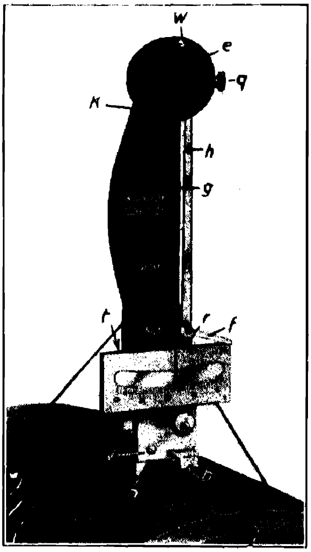

Fig. 39.—A Huggenberger Tensometer.
(Courtesy of Baldwin-Southwark Corporation.)

82. Multiplying Lever Extensometers.—The Huggenberger tensometer is adaptable to a wide variety of strain measurements and especially to ½- or 1-in. gage lengths. The form shown in Fig. 39 has a strain range of 0.008 in. and a multiplication of 1200. The pointer (*g*) is balanced and knife edge fulcra are used. For ½-in. gage lengths the knife edge at (*a*) is reversed. In mounting the device the locking lever (*f*) is released and the pointers (*g*) and (*k*) are set at the proper ends of their ranges as the knife edges are adjusted to the scribed gage lines at (*a*) and (*b*). Care is taken to fasten securely the tensometer normal to the part measured. When the pointer reaches the limit of its range it can be reset by the screw (*g*).

An apparatus embodying both a multiplying lever and an indicating dial is the Berry * strain gage shown in Fig. 40. This device is particularly well adapted to the measurement of deformations in portions of a structure. Any number of measurements on different portions of a beam, column or floor may be made with one instrument provided a pair of $\frac{1}{20}$ in. holes, spaced the gage length of the apparatus apart, are drilled a short distance into each element at the proper place. In measuring, the left pivot which is rigidly attached to the invar-steel side bars is placed in one of the holes and the right pivot, which terminates the short arm of a five-to-one bell-crank lever, is adjusted to the other hole. The long arm of the bell crank rests against the pin of an Ames dial reading to 0.001 in. The instrument is placed in the pair of holes several times and the average reading of the dial noted; the load is changed and the reading repeated. By exercising great care readings accurate to 0.0001 in. may be taken with this device. Side bars for 2, 8 and 20 in. gage lengths can be procured with this instrument.

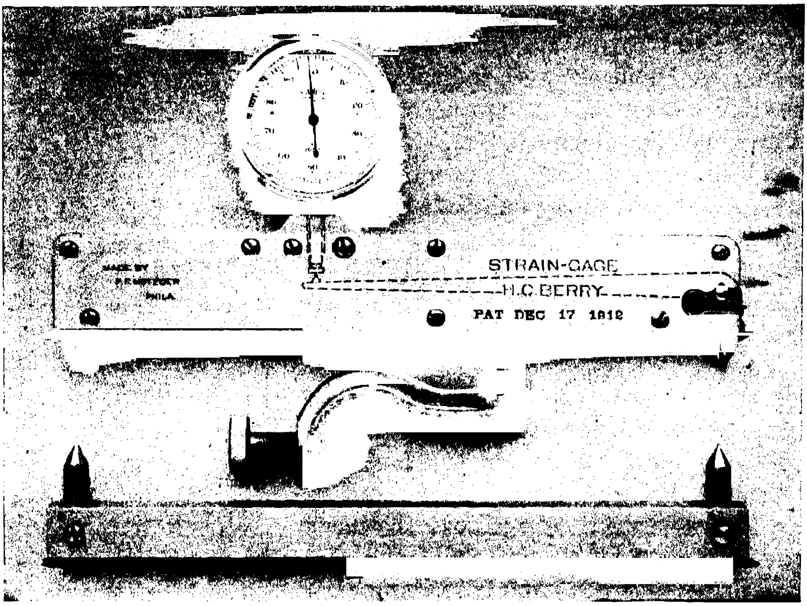

FIG. 40.—Berry Strain-gage for Measurements over 8-inch Lengths, Clamp for Attaching Apparatus to Specimen and Center Punch.

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* Described in *Eng. Record*, June 11, 1910.

83. Martens' Mirror Extensometer.—For greater refinement than 0.00005 in. in the measurement of deformations some form of optical lever is generally employed. One of the most accurate and adaptable instruments is the mirror apparatus devised by Martens. The sketch of this apparatus, Fig. 41, indicates the principle of operation. In this instrument the multiplying levers shown in Fig. 39 are replaced by small mirrors, (4) (Fig. 41), which are attached to the rhombic fulcra (3) so that the axis of each fulcrum passes through the reflecting plane of its mirror. The deformation of the specimen causes slight rotations of the mirrors. The latter are determined by observing successive positions of the cross-hairs in the telescopes (5) with respect to the images of the scales (6), thus finding e_r and e_l.

A better idea of the arrangement of the fulcra and mirrors can be gotten from Fig. 42, which presents a view seen from the telescope. The mirrors (7) may be adjusted about a vertical line through the pivots of the frames (8) by means of screws (9). The springs (10) hold the mirrors against the screws. The mirrors may also be turned about the spindles connecting them with the fulcra (11). To balance the weight of the mirror each fulcra is provided with a counterweight (12). By making the vertical arms (13) parallel to the bars (1), the positions of the fulcra (11) may be accurately adjusted to the gage length for which bars were designed

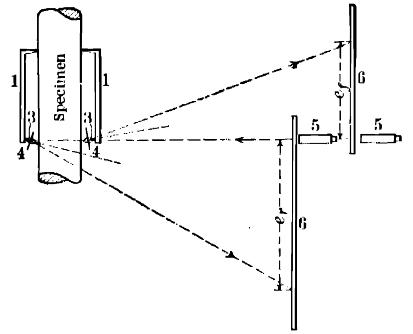

Fig. 41.—Diagrammatic Sketch of Martens' Mirror Extensometer.

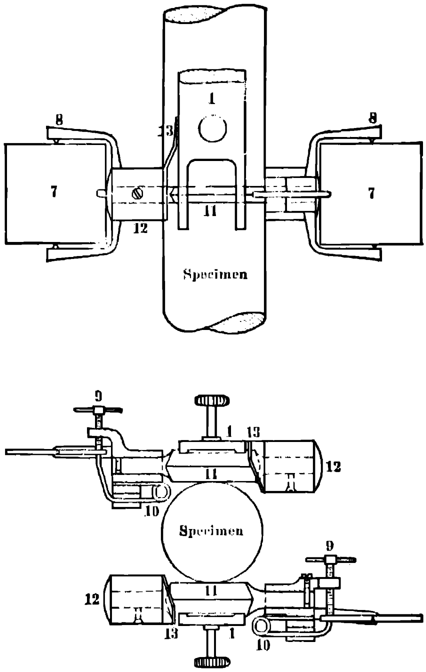

Fig. 42.—Fulcra and Mirrors of Martens' Extensometer.

The entire apparatus is very light and may be quickly placed upon the test-piece. If a flat scale is employed, proper correction to the readings must, of course, be made. With careful handling readings to 0.000002 in. can be taken with this instrument.*

84. Autographic Stress-diagram Appliances.—A number of devices have been employed for obtaining autographic or semi-autographic stress-diagrams. The great objection to many of these devices has been that they involved so many moving parts that they were too complicated to be practical, and the inertia and friction of the parts produced inaccuracy. It is not likely that any of these devices are accurate enough to determine the modulus of elasticity, but some of them are satisfactory for determining the elastic limit, the yield point, the ultimate strength, and the shape of the stress-deformation curve.

The device shown in Fig. 43 † is of the semi-autographic type, and is built so that the accuracy of the strain measurement can be made as great as is desirable. The stress measurement is more approximate and depends on the movement of the poise on the weighing beam of the testing machine. The purpose of this device is to determine the elastic limit and yield point, but not the complete stress-deformation diagram.

Essentially the device consists of a mechanism which punches a pin hole in a card attached to the weighing poise. The card moves horizontally with the poise in proportion to the load, while the punch is moved vertically by a pawl and rack over equal distances, corresponding to equal increments of strain in the specimen.

The operator watches the extensometer which is attached to the specimen, and pushes a button when predetermined equal increments of deformation are noted. The mechanism then automatically punches the card, and next causes an upward movement of the punch. The equal vertical distances between punch marks are proportional to the equal increments of deformation, and the horizontal distances are proportional to the stress.

W. E. Dalby ‡ has designed an optical load-extension indicator which eliminates some of the errors commonly met with in autographic devices, and by means of which the complete stress-strain diagram may be obtained. The extension of a standard bar in series with the specimen is used to measure the load, the extensions of both standard bar and specimen are multiplied by optical levers, and the extension of the standard bar is measured at its axis to prevent errors due to unequal extension and bending.

Figure 44 shows diagrams of the apparatus. The standard bar, *W*

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* For a more complete description and discussion of the Martens' mirror apparatus see Martens' *Handbook of Testing Materials*, translated by G. C. Henning. (Out of print.) The apparatus is made by J. Amsler-Laffon & Sons, Schaffhausen, Switzerland.

† *Proc. Amer. Soc. for Test. Mat.*, 1920, p. 361.

‡ *Proc. Royal Soc.*, Vol. 86A, 1912, p 414.

(shown also to an enlarged scale), is bored out to take the optical apparatus for magnifying the extension of this bar. A small concave mirror, *M*, is free to turn about the axis joining points 1 and 2. A light steel tube, *t*, tilts the mirror, *M*, when the standard bar, *W*, is deformed.

A beam of light starting from the source, *Z*, is reflected by the fixed mirror, *Q*, onto the mirror, *M*, from which it is reflected by the mirror, *N*, and then is brought to a focus on the photographic plate, *F*. The spot of light, therefore, moves horizontally across the plate due to the tilting of the mirror, *M*, in proportion to the load on the specimen.

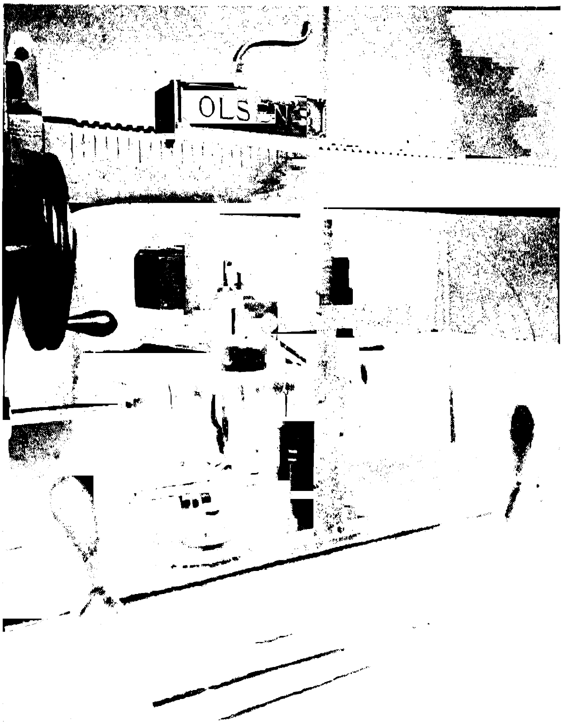

Fig. 43.— Marshall Elastic Limit Recorder.
(Courtesy of C. H. Marshall.)

To obtain vertical movement of the spot of light proportional to the extension of the test specimen, *P*, the mirror, *N*, is mounted on an axis placed at right angles to the axis 1/2 about which the mirror, *M*, turns. The axis of *N* is connected to the specimen, *P*, by means of a linkage.

A frame, *f*, carries the two lower points which are forced into the specimen, and a frame, *G*, carries the two upper points. The frame, *G*, carries a bell-crank lever, *L*. The movement of the bell-crank is transmitted to the link, K, the hanging lever, V, and the coupling rod, U, to an arm clamped onto the axis of the mirror, N. Deformation of the specimen causes tilting of the mirror, N, and the spot of light travels vertically on the photographic plate in proportion to the extension of the specimen.

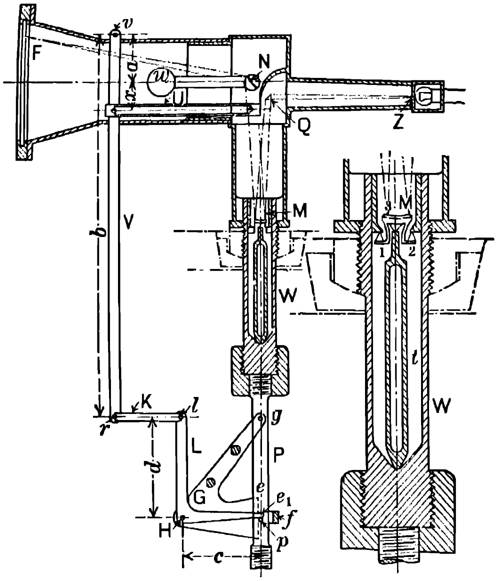

Fig. 44.—Diagram of Dalby's Autographic Load-extension Indicator.
(From *Engineering*, London, Vol. 103, p. 479.)

This apparatus is very easy to calibrate with the specimen in place, both for load and deformation of specimen. Tests can be made at any convenient speed, and complete load-extension diagrams have been obtained with this apparatus in rapid tests which took place in 10 seconds.

COMPRESSOMETERS

85. Essential Features of Compressometers.—The conditions mentioned under essential features of extensometers apply with equal force to compressometers; and the use of an apparatus which measures the relative displacement of the bearing surfaces on either end of the specimen should never be permitted if the modulus of elasticity of the test-piece is sought.

86. Brief Discussion of Various Types of Compressometers.—Inasmuch as the principles of measurement are the same for both extensometers and compressometers, only types of the latter in which the method of attachment differs from that employed in the previously illustrated extensometers will be considered.

Figure 45 shows an indicating dial compressometer used at the University of Wisconsin, primarily for tests on concrete cylinders and wood prisms. It is equipped with two 3-in. Federal dials with adjustable scales reading directly to 0.0001 in. The collars are split and have three-point contact with the specimen. The gage length can be easily varied by changing the length of the rods. The gage bar is removed prior to test. Modification of the collars permits use for measuring strains in columns.

In Fig. 46 is shown a wire-wound dial compressometer also often used at the University of Wisconsin in testing cylinders and columns. The split rings at the top and bottom have three-point contact and dials may be mounted on these to measure deformations along two or more lines parallel to the axis of the test-piece. This apparatus also measures to 0.0001 in.

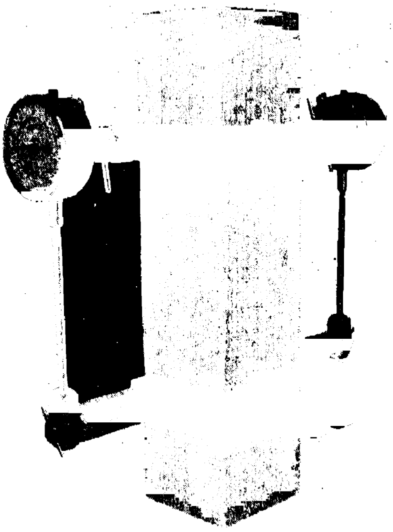

Fig. 45.—An Indicating Dial Compressometer.

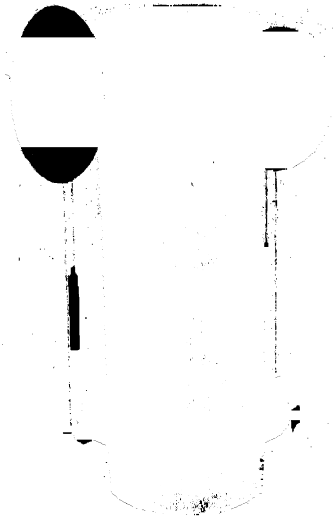

Fig. 46.—A Wire-wound Dial Compressometer for Cylinders and Columns.

Deflectometers

87. Essential Features of Deflectometers.—To measure bending of beams, columns, floors and other elements of structures an instrument called a deflectometer is employed. The essential conditions which should obtain in a deflectometer designed for accurate measurements are:

1. The apparatus should indicate the relative deflections of points in the neutral surface of the member. In many forms of deflectometers

the apparatus itself is suspended from the neutral surface at four points directly above the supports and the deflections measured with respect to a plane through the points.

2. The parts of the deflectometer forming the datum to which the deflections are referred should be unstressed. This principle is often violated. A common practice is to measure deflections with reference to the bed of the testing machine, assuming this to be rigid (see Fig. 48).

3. Provision should be made for determining the deflections of both sides of the test-piece.

4. For most work an apparatus which is sensitive and accurate to 0.001 in. will be found satisfactory.

88. A Dial Deflectometer.—Fig. 47 represents a dial deflectometer which has proven to be a very satisfactory instrument for measuring small deflections. The side bars (1) forming the datum plane of the device are freely supported on pins driven into the neutral surface above the end bearings. To prevent the bars from rubbing against the sides of the specimens washers (2) are inserted as indicated. Clamp (3) holds the side bars in place and prevents them from vibrating during the test. Yoke (4) is clamped by means of thumb-screws to the neutral surface at the point whose deflection is to be measured. In transmitting the motion of the yoke to the dial on the side bars, use is made of No. 38 covered copper wire. One end of the wire is attached to the pin (5) driven into the side bar shown at the right of the sectional view. The wire is then carried around the three idler pulleys (6) and wrapped around the drum of dial (7). Weight (8) serves to hold the wire taut. If the parts of the apparatus are properly arranged the increments in dial readings will be twice the deflection of the beam. If the deflection of each side is desired the device can be readily modified to meet such requirement. With this instrument readings of deflections to 0.0001 in. may be made.

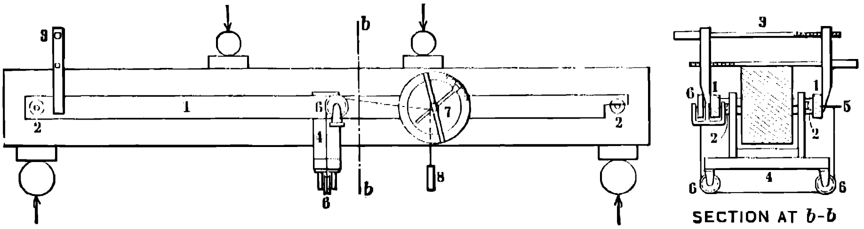

Fig. 47.—Wire-wound Dial Deflectometer Used at the University of Wisconsin.

89. Multiplying-lever Deflectometer.—Fig. 48 illustrates a common type of lever deflectometer reading to 0.001 inch. Frequently, this device is so arranged that the movement of a point on the lower side of the beam with respect to a point in the base of the testing machine is gotten. Unless the deflection of the base of the machine is known to be of no consequence, allowance should be made for it. Furthermore, the indentation of the specimen at the supports enters into measurements made in this manner.

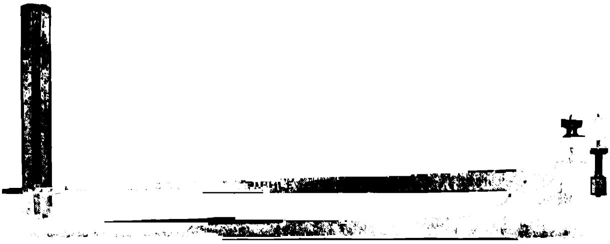

Fig. 48.—A Multiplying Lever Deflectometer with Adjustable Short Arm.

Other convenient devices employing the lever principle are illustrated in Fig. 9 and Fig. 10.

90. A Wire-mirror-scale Deflectometer.—A very simple and convenient form of deflectometer for tests in which large deflections are to be measured is indicated in Fig. 49. In careful work the opposite side of the beam should be equipped with a duplicate of the appliance shown.

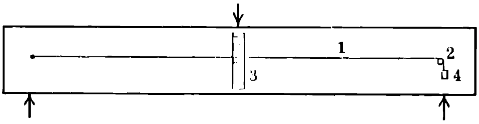

Fig. 49.—A Wire-mirror-scale Deflectometer.

The fine wire (1) which passes over pulley (2) and is kept taut by weight (4), is attached to pins placed in the neutral surface above supports and forms the datum from which the deflections are measured. The highly polished scale (3), ordinarily graduated to 0.01 in., is also suspended from the neutral surface. In reading, the observer brings his eye into the plane of the wire and its image and notes the division intercepted on the scale.

Beam Deformeters

91. Wire-wound Dial Deformeters.—The device illustrated in Fig. 50, which is a modification of the extensometer in Fig. 36, is employed to measure the deformations in the longitudinal fibers of a beam. Generally such measurements are made upon the top and bottom fibers. If fibers nearer the neutral surface are to be measured, deeper U-shaped clamps must be provided.

92. Other Types of Deformeters.—Many experimenters have employed apparatus of the type shown in Fig. 51. Some have replaced the micrometer-screw by dials with friction rollers. An objection to the form of frame shown is that free motion of the upper and lower points of contact is restricted more or less depending on the rigidity of the frames.

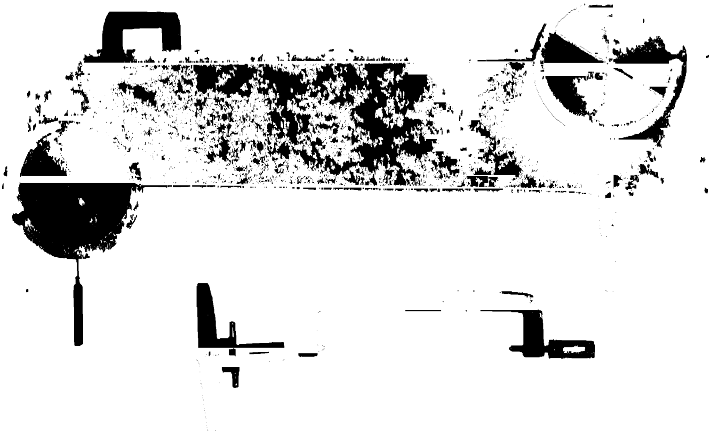

Fig. 50.—Wire-wound Dial Deformeter Device Used to Measure Fiber Stresses in Beams

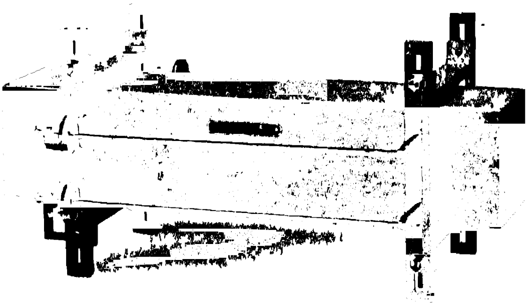

Fig. 51 Micrometer-screw Deformeters

The Berry strain-gage shown in Fig. 40 is a very useful device for measurements of all sorts of deformations in beams.

DETRUSION INDICATORS

93. Porter's Detrusion Indicator.*—Essentially, this apparatus consists of two rings, each of which is clamped to the specimen by three set-screws, see Fig. 52. The distance between the rings is fixed by gage bars provided with studs for centering the test-piece. The right-hand ring is graduated in degrees and supports, on a ball-bearing, a concentric ring provided with a vernier reading to 5 minutes. The vernier ring is moved by a finger attached to the left-hand ring In order that the

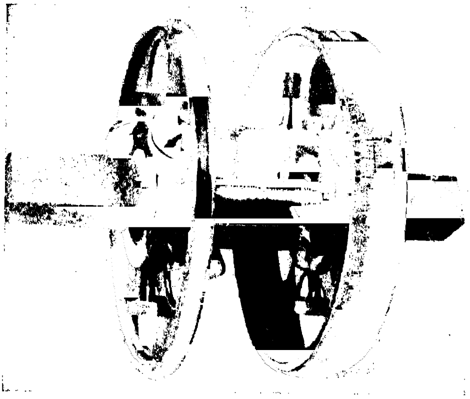

FIG. 52.—Porter's Indicator with Distance Bars in Place.

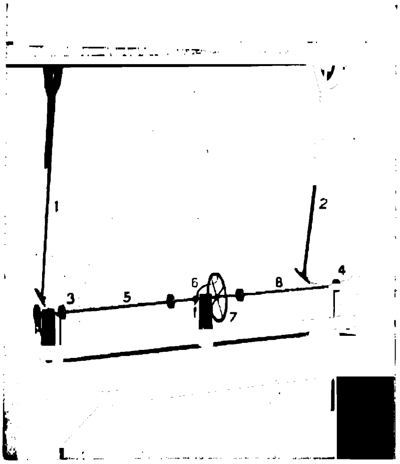

FIG. 53.—Torsion Indicator Used at the University of Wisconsin.

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* Described in *Proc. A. S. T. M.*, Vol. 10, p. 578.

parts of the apparatus may be free to move as the specimen suffers change in length, a ball joint is provided to connect finger and vernier ring. For setting the vernier to read zero the connection between the finger and vernier ring is equipped with a slow-motion tangent screw. The instrument shown was made for specimens less than $1\frac{1}{4}$ in. in diameter and a gage length of 3 in.

94. A Dial Indicator of Detrusion.—An apparatus for detrusion measurements which has been in use for several years at the University of Wisconsin is illustrated in Fig. 53. The twist of the section of the specimen between the arms (1) and (2) is transmitted through No. 38 covered copper wire to the drums (3) and (4), respectively. The spindle (5) carrying drum (3) actuates the pointer (6). Similarly dial (7) is connected to drum (4) by spindle (8). From this arrangement it is, therefore, evident that the twist between the two sections of the specimen can be gotten by noting the relative positions of pointer and dial corresponding to the increment in torque. In the apparatus shown the multiplying factor is 40, and the dial is graduated in one-half degrees. Any deflection produced by bending of the specimen during the test will, of course, affect the readings of this apparatus. However, a rough computation quickly demonstrates that such effects are negligible.

Miscellaneous Apparatuses for Measuring Deformations

95. Multiplying Dividers.—A very efficient little device for accurately locating the yield point in a tension or compression test is Capp's

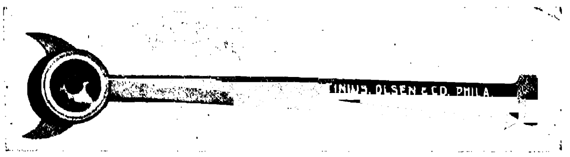

Fig. 54.—Capp's Multiplying Dividers for Detecting the Yield Point.

multiplying dividers, shown in Fig. 54. In performing a test with this instrument, the operator grasps the cupped pivot-heads between the thumb and finger of his left hand and places the hard steel points on the end of the short arms in punch marks spaced 2 in. apart. By this method the operator's right hand is free to move the poise on the scale-beam if the machine is not provided with an automatic drive. For elastic stresses the motion of the pointer over the scale is hardly appreciable, but when the yield point is reached the rapid increase in the rate of motion of the pointer instantly warns the operator of the fact.

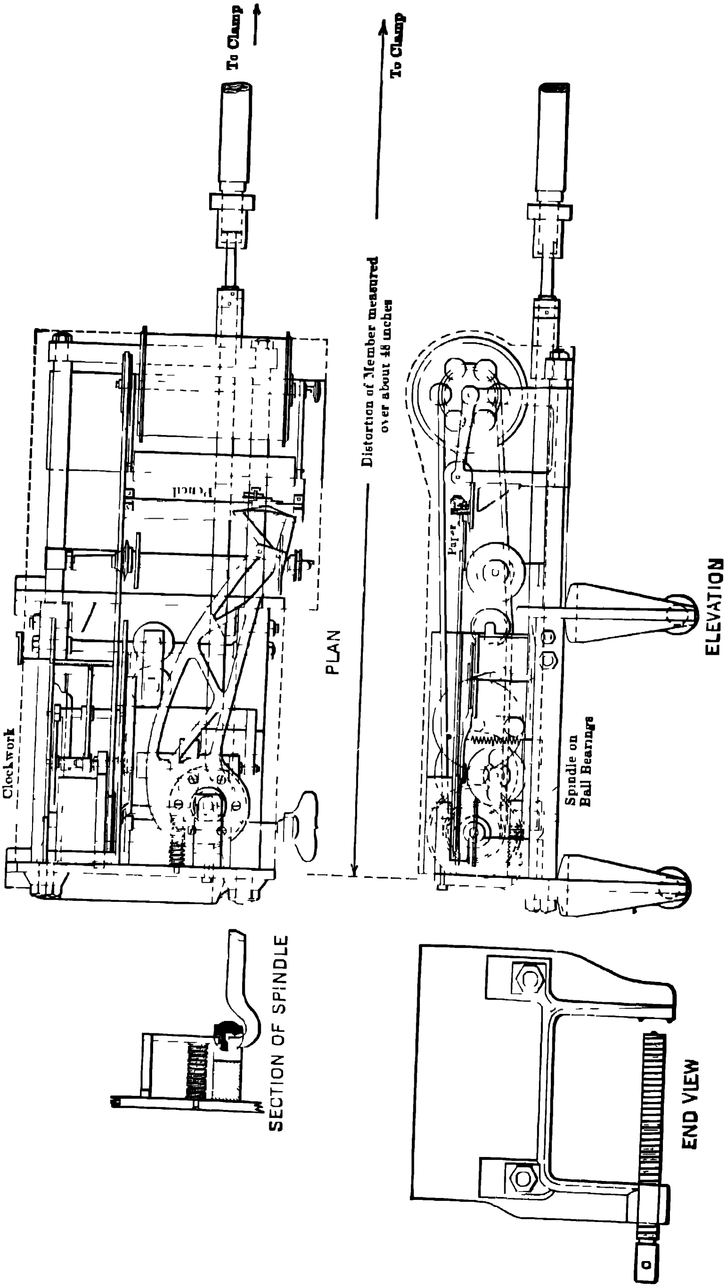

Fig. 55.—A Recording Extensometer for Measuring Deformations in Bridge Members.

With such a device mistakes in the location of the yield point due to slipping of the grips are obviated. In tests of high-carbon steels, wire, and other materials having a high yield point the drop-of-beam method is very uncertain at best. By using the divider method, however, a distinct indication of the yield point can be readily obtained.

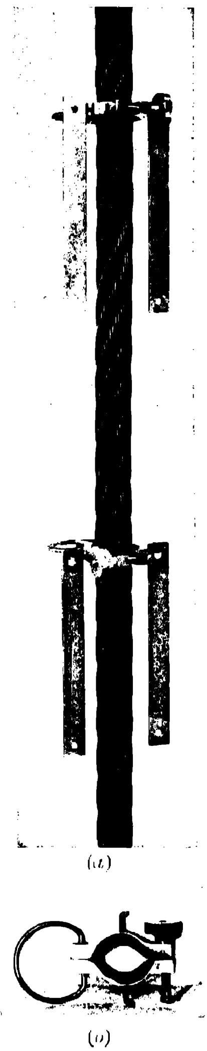

Fig. 56.—A Wire Rope Extensometer. (a) View from Telescope; (b) Clamp for Attaching Scales to Rope.

96. A Recording Bridge Deformeter.— The apparatus shown in Fig. 55 was designed by the Structural Engineering Department of the University of Wisconsin to measure the deformations in bridge members while subjected to moving loads. The movement between the gage points of the apparatus is transmitted through a long rod to a light, rigid lever actuating a pencil point which records 50 times the deformation on the diagram sheet. The latter is wound about the drum which is turned by an electrically controlled clockwork. A number of these instruments were used with success in a long series of experiments by the American Railway Engineering and Maintenance of Way Association.*

97. A Wire-Rope Extensometer.—A simple and durable device for measuring the elongation of wire-rope is illustrated in Fig. 56. Increments of elongation are determined by taking simultaneous readings on the upper and lower pairs of scales by transits or telescopes set up a short distance from the test-piece. The scales are graduated to 0.01 in., and readings to half-hundredths may be established. Twisting of the rope does not materially affect the results if each telescope be placed on a level with the corresponding pair of scales. Furthermore, since the device is not delicate or expensive and the observer well back from the test-piece, readings may be taken until the specimen fails.

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* *Bulletin of American Railway Engineering and Maintenance of Way Association No.* 125, p. 9; also *Engineering News*, June 20, 1907. This apparatus is made by A. Wissler Instrument Works, St. Louis, Mo.

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CHAPTER III

THE MECHANICAL TESTING OF STRUCTURAL MATERIALS

98. General Observations.—Mechanical tests are those used to discover the qualities of the materials of construction under the action of external forces. Such tests, if they are to be of most value, should be made under conditions approximating as closely as possible those of practice. By standardizing these conditions the results become comparable wherever or by whomsoever thay are made and are of very great importance in determining the properties and value of building materials. If such results can be made wholly independent of the means employed in making the tests, and hence to furnish a knowledge of the true characteristics of the material, they can be used safely in theoretical generalizations on the one hand, and in the practical designing of structures on the other. With many kinds of tests this ideal divorcement of the results from the conditions of the tests can certainly never be attained, as in the case of tests by impact, but it doubtless can be practically attained in some of the more simple tests, as in tension and compression. In the former case the most that can be accomplished is to prescribe uniform conditions in order that the results obtained by different experimenters may be comparable, although they may not serve for accurate scientific generalizations. They might also serve to give a relative value to the various materials or samples so tested, and to grade them with some degree of approximation to their true relative merits for a proposed purpose. Such tests, therefore, may serve fully their immediate object even though the results can be given no absolute significance whatever. If, however, the conditions of such tests are allowed to vary, they lose even this relative significance, and therefore become quite worthless. The standardizing of any particular kind of test evidently depends on the state of the science at the time; and as our knowledge of any particular property of a material increases, it is probable that our standard methods of testing will also have to change. No such standards, therefore, can be fixed permanently, but certain methods can be agreed on and followed for a time, and when a change is made let all change together. To attain to this kind of unity of action it is necessary to have a world's representative body which will command the confidence and allegiance of both the theoretical and the practical users of materials in all civilized countries to decide such questions.

The efforts of the International Association for Testing Materials towards securing such unity of action in various countries have not thus far been productive of great reforms, although the outlook is hopeful. Within America, however, the American Society for Testing Materials and the American Standards Association have been successful in standardizing methods of testing and the specifications used in the United States.

Evidently no complete standardization can be effected for tests on entire structural forms, since these vary in shape, size, and disposition of parts, but specimen tests can be standardized since all significant conditions can be made uniform.

99. Mechanical Tests Classified.—In a general way we may divide mechanical tests of building materials into the following classes:

With reference to the method of applying the loads we have—

(1) *Static Tests*, or those made with gradually increasing loads, such as the ordinary tests in tension, compression, cross-bending, torsion, and shearing.

(2) *Dynamic Tests*, or those made with suddenly applied loads, as by a falling weight.

(3) *Wearing Tests*, or those made for determining resistance to abrasion and impact, as in the case of paving-materials.

With reference to the character of the test specimen we have—

(1) *Specimen Tests*, or those made upon specimens of the material, specially prepared and given standard forms and dimensions.

(2) *Structural Tests*, or those made on full-sized structural forms, as floor systems, bridge members, brick piers, pipes, wire ropes, chains, riveted joints, etc., or on the structure as a whole, such as boilers, simple trusses, frames, and various parts of machines.

Complete standard rules for making tests of structural materials can be adopted for making all kinds of tests on specially prepared specimens, but they can be only partially prescribed for tests of structural forms.

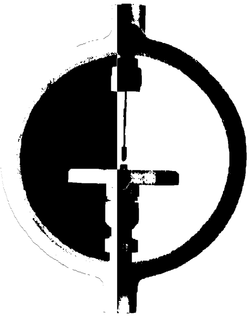
THE ACCURACY OF MACHINES AND APPARATUS

100. Methods of Determining the Accuracy and Sensitiveness of Testing Machines.—General considerations of the accuracy, sensitiveness, and conditions which should obtain in testing machines have been given in Ch. II. Since it is of vital importance that the user of a testing machine should know approximately at least the accuracy of his machine, a brief statement of methods commonly used for testing accuracy and sensitiveness will here be made.

In testing the accuracy of vertical static-load machines five to ten equal increments of dead load can be placed on the platform of the machine, or on extensions formed by I-beams, and the corresponding readings of the weighing device compared with the known loads. After each increment of load has been added the sensitiveness may be determined by finding the additional weight which is required to make a perceptible indication on the weighing device. This method, even when pig iron is used, is too cumbersome and laborious for loads above 10,000 to 20,000 lb. In calibrating machines of the lever type, loads of this magnitude are sufficient to determine the multiplying factor for the lever system and, assuming this factor constant, a correction coefficient applicable to the range of machine may be determined. It is not safe, however, to estimate the sensitiveness at high loads to be proportionately the same as at low loads. In calibrating hydraulic machines in which friction is a factor, it is desirable to test the machine to full capacity.

Standardized calibrating levers, with weights, in capacities up to 100,000 lb. are available. They furnish a more expedient means of calibrating over a greater range of loads than the dead weight method. For procedure in calibrating testing machines, see *A.S.T.M. Standards*.

The comparatively large elastic deformation of a steel ring when subjected to a load in its diametral plane affords a reliable measure of the applied load. Morehouse rings fitted with accurate permanently attached extensometers utilize this principle for calibrating testing machines. Calibrations by the U. S. Bureau of Standards indicate that these devices are accurate to two-tenths of one per cent between two-tenths capacity and full load. Rings with capacities up to 300,000 lb. are obtainable.



A Morehouse Ring.

Amsler boxes in capacities up to 1,000,000 lb. provide compact means for calibrating testing machines. They are said to be accurate to one-half per cent in the upper nine-tenths of their load ranges. The volumetric elastic strain of a hollow cylindrical box indicated by a mercury gage measures the load applied by the testing machine. Hence temperature effects must be eliminated in calibrations.

Calibrated annealed steel bars or compression cylinders of high elastic limit so proportioned that they need not be stressed beyond two-thirds of their elastic limits are used for calibrating large testing machines to capacity. They should be axially loaded and fitted with self-indicating extensometers with gage length and accuracy such that the least reading will correspond to a load change not greater than 0.2 per cent of the capacity of the machine. If a compression cylinder is used, the slenderness ratio should not exceed 20; and, if hollow, the thickness should equal one-eighth of the diameter.

Calibrating test-pieces should be standardized at the Bureau of Standards or on machines of known calibration. Care should always be taken to standardize such a test-piece under the same conditions as will surround the specimen when it is used for calibration purposes. A half dozen or more increments of load may be applied to the calibrating specimen at a speed not to exceed 0.1 in. per minute and corresponding readings of the deformations taken. After each increment of loading, the dead weight required to produce a movement of the weighing device furnishes a measure of sensitiveness.

Pressure gages on hydraulic machines should be frequently calibrated throughout the entire range of loading. If the pressure in the jack is measured to determine load on machine, calibrations under increasing and decreasing loadings should be made with the piston at different positions in the stroke. By so doing variations in the frictional resistances can be determined.

101. The Calibration of Apparatus for Measuring Deformations.—For certain classes of testing, a knowledge of the accuracy and sensitiveness of apparatus used to measure deformations is of as great value as similar information concerning the testing machine. For most purposes an accuracy of 1 per cent is sufficient in such apparatus. Essential considerations for different types of deformation apparatus have been discussed in the preceding chapter. When conditions permit the calibration of such devices may well be left to standard laboratories such as the Bureau of Standards or the Watertown Arsenal. If calibration is done in the home laboratory, the following method serves for a rough test of accuracy and sensitiveness.

The apparatus may be attached to a steel test-piece for which the stress-deformation curve has been accurately determined; and the test-piece gripped in a standard manner by the machine, so that slipping and improper distribution of stress are avoided. Increments of load are very slowly and uniformly applied to the test-piece and the corresponding readings of the apparatus taken. After each increment of loading one may determine sensitiveness by observing the increase and decrease in load required to produce a readable change on the deformation apparatus.

If a standardized deformation apparatus is at hand, it may also be attached to a specimen under conditions similar to those surrounding the apparatus which is being calibrated. The unknown device can then be compared with the standard under loading conditions indicated above.

A more accurate method than the above for calibrating extensometers and compressometers consists in clamping one end of the apparatus to a dummy specimen held in a lathe chuck and the other end to the centering spindle of the tail-stock. By using a microscope with a standardized micrometer eyepiece the movements of the pivot end of the spindle can be determined and compared with readings of the motions registered by the deformation apparatus. If a precision lathe can be had, one part of the extensometer may be attached to the spindle on the tailstock and the other to a specimen held on the lathe carriage. In this setup the axes of specimen and spindle should be colinear. The lathe may then be set so that the carriage travels .02 or .01 in. per revolution of the chuck and a comparison of the deformation apparatus with the lathe screw determined.

Using a standardized linear dividing engine, reading directly to 0.002 mm. or less, still greater refinement may be obtained. With such apparatus it is possible to calibrate scales, micrometers, and practically all of the devices used in measuring deformations.

When calibrating apparatus in which accuracy in fabrication is based directly or indirectly upon the accuracy of a screw, readings of say one-tenth the range should be taken over the entire range of the apparatus to determine the cumulative error of the device. Periodic errors may be ascertained by a large number of readings of small increments of motion over a limited portion, say one-tenth, of the range. Furthermore, to eliminate periodic errors in the calibrating device it is essential that the apparatuses under comparison be shifted several times and the entire range and partial range calibrations repeated.

To avoid errors due to lost motion in screw-calibrating devices one must always approach the desired reading from the same direction. To accurately detect lost motion or lag and to determine the sensitiveness of the deformation apparatus, observations on minute forward and back motions of the moving part of the apparatus may be made under a microscope provided with a micrometer eyepiece.

SELECTION AND PREPARATION OF SPECIMENS

102. Selection of Specimens.—It must be recognized at the outset that specimens are selected for testing with either of two objects in view—to compare the mechanical properties of certain materials or grades of the same material, or to ascertain the influence of certain conditions of fabrication, treatment and usage on the mechanical properties. In comparing mechanical properties the size, shape, method of fabrication, and subsequent treatment of the specimens are generally standardized, but in ascertaining the effects of structural conditions one or more of these is made variable. When choosing specimens for any kind of test the inspector must constantly bear in mind that the test results are valueless unless the specimens are truly representative of conditions and properties under investigation.

The numerous specifications of the American Society for Testing Materials, American Society for Mechanical Engineers, the Society of Automobile Engineers, American Railway Engineering Association, and others, in general, cover the method of selecting test specimens of metals and metal elements which are to be used for various purposes. Test-pieces may be cut from the finished casting or rolled product. If the quality of metal is to be ascertained, specimens of cast metals should be separately poured into vertical dry molds. If specimens are cut from castings, it must be remembered that shrinkage strains exert a pronounced effect upon strength at all corners and angles in the casting and that the outside, especially in cast-iron members, is often much stronger than the center. When specimens are cut from rolled structural shapes, one should consider that the metal in thin parts is harder, tougher, and stronger than that of thick portions which has received less work under the rolls. With wrought iron especially, specimens cut with the direction of the rolling are stronger and more ductile than those cut normal to the rolling. In steel plates there is little difference, and in rolled brass and copper plates there is no difference. In the case of the bronzes it is necessary to have test samples poured from different parts of the same melting, as the mixture changes its characteristics rapidly when in a melted state.

Piles of brick or building tile may be subdivided into small piles and one or two samples representing each small pile chosen. In selecting samples, color, depth of kiln-mark, number and position of checks and spalls, and ring under the hammer should be considered. If the sampling is done at the kiln, the position of the specimens with respect to the source of heat must be considered.

Specimens of stone should be selected from the different strata which are being worked. If the surface has been exposed to the weather for a considerable time, specimens should be cut from the interior. The faces of specimens should be referenced with respect to the rift in the rock. Portions of rock adjacent to blast holes should be avoided.

In selecting timber specimens, the rate of growth of the tree as told by the annual rings, position in the tree, the proportion of heartwood and sapwood, the proportion of spring and summer wood, the moisture content, the method of seasoning, and the character and position of defects must all be considered. (See *A.S.T.M. Standards*, Des.: D143–27.)

The number of specimens to be selected to secure a representative average for a material will depend both upon the uniformity of the material and the uniformity of testing. *Two* or *3* specimens are sufficient for a tension test of a uniform metal whereas *5* to *10* is a better number for compression tests of a variable masonry material requiring bedment. If $n =$ the number of specimens such that the chances are 1 in 10 that the average of n will be in error less than x per cent and $d =$ the standard deviation of a large number of specimens (>100) from their average, then from the laws of probability* $n = (1.64d/x)^2$. Hence if $d = 15$ and $x = 10$, $n = 6$.

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* See paper by R. W. Crum on the number of specimens required for such materials, in *Significance of Tests of Concrete and Concrete Aggregates*, A.S.T.M. publication, 1935.

103. The Preparation of the Specimen.—In order that the specimen may fairly represent the material, plate, bar, or rolled form from which it is to be taken, it is necessary to observe a number of requirements.

The specimen must be obtained by cutting it out in a way that will leave it perfectly straight. If a metal test-piece is bent in getting it out, it should be heated to straighten it; but this may often change the original molecular arrangement, and should be avoided if possible. When the specimen is cut from a larger portion of a plate or rolled form by shearing, it will invariably take a curved form. In this case *the plate, or form, should be sheared away from the specimen,* in narrow slices, so as to leave the test specimen unbent. If the specimen is bent and then straightened, it raises the elastic limit and hardens the metal, the same as any other kind of cold working. Instead of shearing, some milder process, such as planing or drilling or sawing, should be resorted to to obtain the test specimen. For, besides the bending action on the bar as a whole, the effect of the shearing or punching is to embrittle the metal for about an eighth of an inch beyond the sheared surface, hence under a tensile test these surfaces will be severed causing a premature failure of the remainder of the cross-section. To prevent this action on sheared or punched specimens, at least an eighth of an inch of thickness should be removed from all punched or sheared faces, by reaming, planing, or filing.

Final finishing of hard metal specimens should be done with a file in order to avoid the torn and bruised surface conditions which result from the use of lathe and planer tools. Soft metal test-pieces should be finished with emery cloth. If the skin is removed from a casting by planer or milling device, it is well to remove the rectangular corners with a file in order that incipient cracks or irregularities caused by the tools may be eliminated. If soft metal specimens must be straightened, wooden or copper mallets should be employed; a steel hammer should never be used. The ends of metal compression specimens should be accurately ground to parallel plane surfaces.

To avoid the inclusion of material which may have been weakened in quarrying, it is necessary to saw compression test-pieces of stone from the interior of blocks somewhat larger than the test-pieces: roughing out the specimen with hammer and chisel may cause a large reduction in strength. If the latter method is permitted, care should be taken to make the sides of prismatic specimens plane. If accurate results are desired, it is well to grind to true planes the surfaces which are to be subjected to pressure. Specimens of brick, building tile and concrete will show greater strength if similarly treated. Since the expense of this work is often prohibitive, bedments such as are described in Art. 76, 77 and 78 are often used to overcome the effects of surface inequalities.

TENSION TESTS

104. Significance of Tension Tests.—Tension tests are more common, more readily made, and more useful in revealing the true character of a metal than any other kind of mechanical test. In fact, when other kinds of tests are made it will commonly be well to accompany them with a few tensile tests for the purpose of being able better to co-ordinate the results with those obtained on other materials by similar tests, or on like materials by different tests. In this connection, however, it is well to remember that all metals are wanting in strict homogeneity, and that they may be regarded as aggregations of more or less dissimilar elements embedded in a common matrix, somewhat like granite. (See Art. 623 and 663.) For instance, the planes of rupture will be different for different kinds of tests on the same specimen, and hence the strength developed will be that of a different combination of elements in each case. Also, the strength to resist various kinds of stress may lie in different elements of the aggregation, as, for instance, in gray cast iron the tensile strength is dependent both on the proportion of free graphite flakes and on the strength of the impure iron grains, whereas the compressive strength is primarily dependent upon the strength of the iron grains.

What we call the maximum strength of the material, therefore, or its strength at rupture, is not usually the sum of the maximum resistances of the several elementary portions of the cross-section, since they do not all distort equally. It is often the case that actual rupture occurs successively over many elementary portions of the broken section before the final failure occurs. More especially is this true of the elastic limits of the material, while with iron and steel castings this failure in detail is so prominent as to cause the stress-diagram to be a curve almost from the beginning of the loading. Here, too, the irregular shrinkage often leaves very great internal stresses in the body, which causes some portions to come to their elastic limits and ultimate strength much earlier than others, again giving rise to a curved stress-diagram.

The tension test is especially well calculated to show what local irregularities may be found in a finished product, and to indicate to what extent the work of forging (rolling or hammering) has produced that degree of homogeneity expected of it.

The tension test is more readily standardized than any other so as to be independent of "personal equation" and of variations in the testing-machines employed. It also demands the least amount of preparation of the test specimen, if tests are to be made only for commercial purposes. Except for the inherent want of uniformity or of homogeneity mentioned above, therefore, the tension test may be made to give typical and uniform results, and it should be considered as the best single test to make on any of the metals. The A.S.T.M. Standard Methods of Tension Testing of Metallic Materials, Des.: E8-36, will be of much value to students of this subject.

COMMERCIAL TENSION TESTS

105. Object.—In routine tension testing of metals the ultimate strength, yield point, and per cent elongation are always determined, and usually the per cent reduction in area and the character of fracture are noted. From these properties the tensile strength, the limiting working unit stress, and the ductility are ascertained; the modulus of resilience and energy of rupture, both measures of toughness, can be computed; and the homogeneity and structure of the metal are judged. Therefore, such tests, performed speedily and cheaply, serve a very useful purpose.

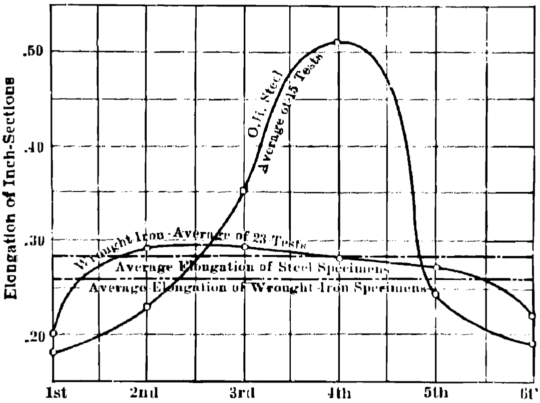

FIG. 1.—The Variation in the Distribution of the Elongation of the Several Inch Spaces of Six-inch Test Bars of Steel and Wrought Iron 0.56 In. in Diameter. (*Tests of Metals*, 1890.)

106. Types of Tension Specimens—Experiments have shown that the form of a tension test-piece has an influence upon both the strength and elongation. The influence on strength of grooving and sudden contractions in area is considered in Arts. 719 to 721. Fig. 1 shows the variation in unit elongation for successive spaces on steel and wrought-iron bars. Fig. 2 illustrates the influence of the length of the gaged position on per cent elongation.

Tetmajer proposed that the elongation due to the neck be eliminated by subtracting the elongation in a 4-in. from the elongation in an 8-in. gage length and dividing by the difference in the gage lengths. The function, thus obtained, would be independent of the gage length of the specimen. This proposal has not, however, been widely adopted.

On account of the above considerations it has become quite necessary to prescribe certain types of specimens for commercial tests in which the grading and acceptance of material is involved. M. Barba * has shown that the resistance and per cent elongation remain constant provided the *relative* dimensions are not changed and the method of gripping and loading are identical. As the result of his work and a large number of tests, the French Commission adopted the relation $l^2=66.67A$ or for cylindrical specimens $l=7.2D$, where l is the measured length on which the elongation is computed, D is the diameter, and A the area of cross-section. The German Commissions use $l=11.3\sqrt{A}$, which is equal to $l=10D$ if the specimen is cylindrical. Engineering societies in the United States have not rigidly adhered to either of these rules, or even Barba's law, in standardizing the shape of test-pieces cut from plates or other rolled sections. However, they have prescribed fixed standards for cylindrical and flat specimens (see Figs. 3c and 3e). For flat specimens over $\frac{1}{4}$ in. thick, the gage length is 8 in. and the width $1\frac{1}{2}$ in. The width of specimens cut from material less than $\frac{1}{4}$ in. in thickness must be five times the thickness with a minimum of $\frac{3}{4}$ in., and the gage length must be twenty-four times the thickness with a minimum of 2 in.

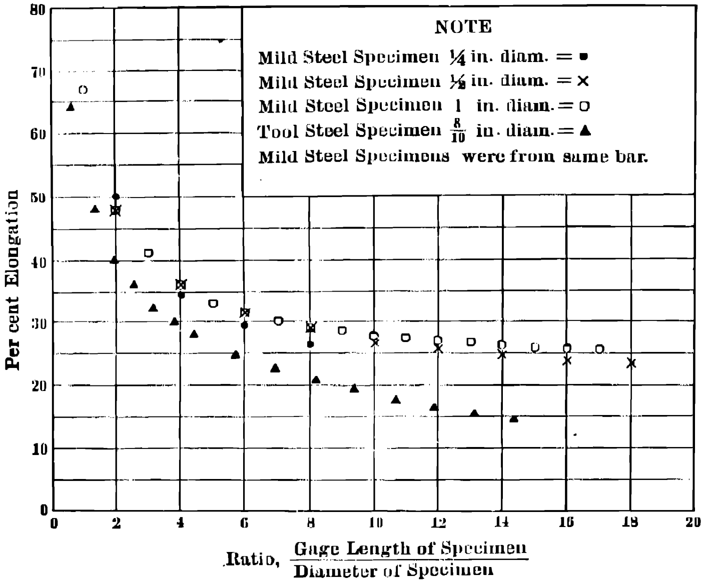

FIG. 2.—The Influence of the Ratio $\frac{\text{Gage Length}}{\text{Diameter}}$ on the Per Cent Elongation of Steel Specimens.

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* *Mem. de la Société des Ing. Civils*, 1880, I, p. 682. See also Unwin's *The Testing of Materials of Construction.*

In Fig. 3 are shown seven types of specimens dimensioned in accordance with practice. For rough tests on ductile rounds or flats, form (*a*)

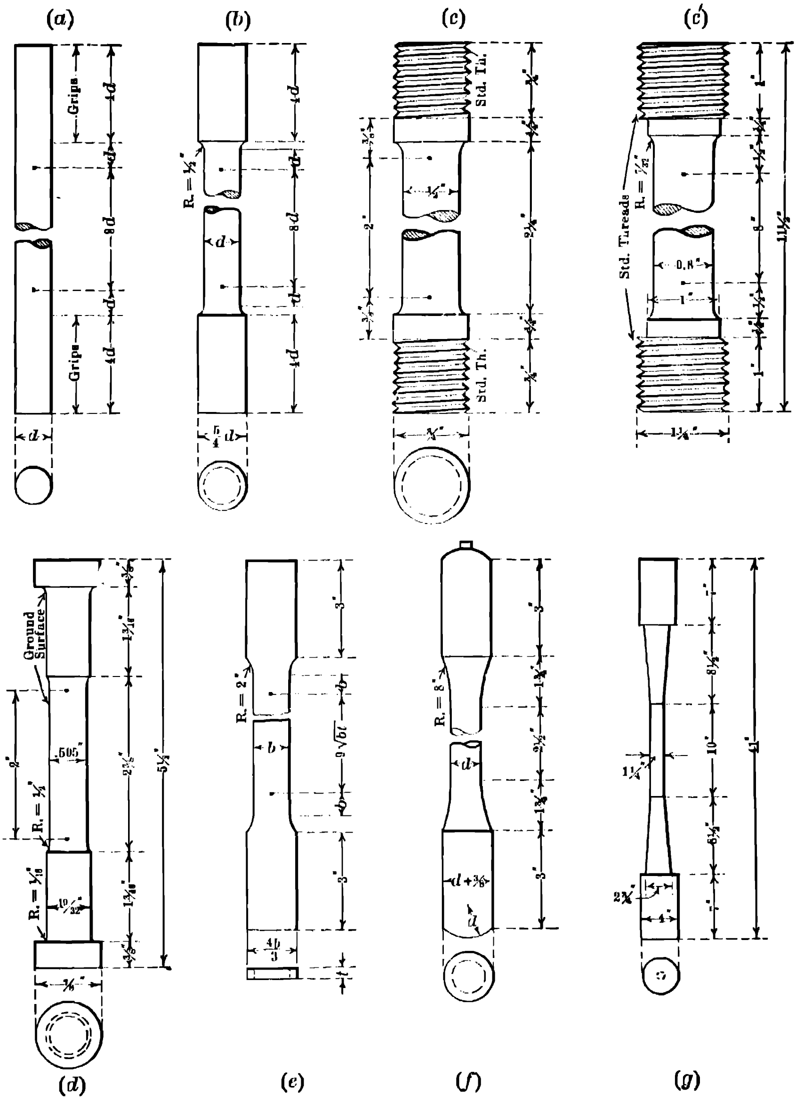

FIG. 3.—Types of Specimens for Tensile Tests.

is suitable. Form (*b*) is a more expensive specimen which is less liable to slip in the grips and also receives a lower intensity of compression from the grips than does form (*a*). For more careful tests in which it is highly desirable to avoid slipping at the grips, form (*c*) or (*c′*) is used in conjunction with the holder shown in Fig. 29, Art. 69. Automobile steels of very high elastic limit and great hardness cannot be readily fashioned into form (*c*) after hardening. If so fashioned before heat treatment, these steels are liable to become warped and weakened at the screw threads. For such steels form * (*d*) may be used in connection with the holder shown in Fig. 30*b*, Art 69. An inexpensive casting which makes a very satisfactory test-piece for rough tests on cast iron, malleable iron and similar brittle metals is form (*f*). Form (*g*) has been used with success by Prof. W. H. Warren of Sydney University, Australia, in testing the tensile strengths of woods.

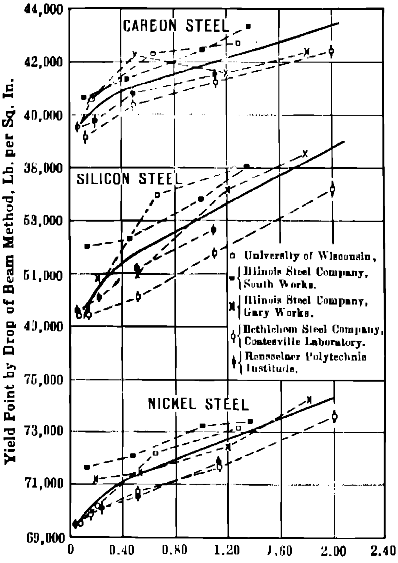

FIG. 4.—Effects of Speed of Machine on Yield-Point of Hot-rolled Steel Rods. (Rept. of Research Committee on Yield Point, *Proc.* A.S.T.M. 1928.)

107. Testing.—The dimensions of cross-section of the specimen are measured at several places along the gage length. If the test-piece is cylindrical, mutually perpendicular diameters should be measured at each cross-section. Measurements of metal should be accurate to $\frac{1}{4}$ of 1 per cent. The average cross-section of deformed bars can be computed from determinations of weight and length.

The specimen is then placed in a V-block and punch-marked at intervals of 1 inch along the entire gage length. A laying-off gage or a multiple punch is a time-saver in this operation. Fine wire and sections which would be weakened by punching may be marked with ink.

Although speeds of head up to 3 in. per min. have little effect on the ultimate strength and elongation of hot rolled steels, the data of Fig. 4 for rods with a free length between grips of 10 in. show that the yield point is affected considerably by speeds of head above $\frac{1}{4}$ in. per min. Data from the 1937 report of the same Committee indicate that for serrated grips the rate of straining or stressing increases very rapidly with the load. These considerations led the Committee to recommend that the rate of straining or stressing be limited during such tests. Tentatively a rate of straining of 0.0015 in. per in. per min. and a rate of stressing of 45,000 lb. per sq. in. per min. were suggested as maximum rates for determinations on the yield point of structural steel. In testing specimens of 8-in. gage length with serrated grips a speed of about 1 in. per min. may be used to three-fourths of the estimated yield point, the proper rate of straining or stressing imposed until the yield point of yield strength is obtained, and finally a speed of 2 in. per min. applied to rupture. For cast iron and similar brittle materials the speed throughout the test ought not to exceed 0.02 or 0.03 in. per min. per in. of gage length. The speed should be constant for any given series of tests.

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* See description of this type of specimen by K. W. Zimmerschied in *Trans. Soc. Auto. Engr.*, Vol. 8, pt. 2, p. 161; also see Marten's *Handbook of Testing Materials*, p. 10.

The French Commission recommends that tests be continuously progressive; that the duration of test be proportional to the volume of the specimen (one to six minutes for ordinary sizes of specimen, less than thirty seconds for test-pieces under 0.2 in. thick); that heating of the bar must be avoided, especially with the softer metals.

In tests of high-carbon steels and in tests in which there is slipping at the grips a pair of Capp's multiplying dividers (see Art. 95) will be found useful.

108. Observations for Record.—The record should contain sufficient information so that the history of the specimen previous to the test may be traced. In inspection at the mill this includes heat number, specimen number, and such other information as may be needed to reference the specimen to the portion of the heat or to the member from which it was taken.

The first sign of weakening at yield-point of the specimen should be carefully ascertained. In wrought iron and the low-carbon steels this is readily determined by the drop of beam, by the rapid increase in motion of the divider pointer and, in rolled material, by scaling. If rolled bars of uniform cross-section are used, the scaling will appear first at the grips, owing to the combined stress existing there, and gradually extend toward the center of the specimen. It will be noted that the scaling advances on lines at about 45 degrees with the axis of the specimen: i.e., on the surface traces of the planes upon which maximum shear stress exists. Of these, the divider method is the most reliable index of the yield point, with drop of beam a close second.

The maximum load is next determined. It will be found to occur simultaneously with the commencement of the "necking down" action in ductile materials, with rupture in brittle materials. After rupture the test-piece is again laid in the V-block with the fractured ends in contact and a record of the length of gage across break is made. Methods of measuring the elongation when the fracture is near the end of the gage length are given in *A.S.T.M. Standards*, Des.: E8–36.

If the specimen has a " cup and cone" fracture, it is best to join the fragments and measure the diameters of the minimum section with a screw-thread micrometer. The reduced areas of rectangular specimens can be most readily determined by measuring b, d_1 and d_2 as shown in Fig. 5. To measure fractures of irregular outline, a micrometer provided with a conical spindle and anvil will be found convenient.

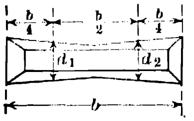

Fig. 5.—Reduced Area of a Rectangular Test-Piece $= b\frac{(d_1+d_2)}{2}$.

Two characterizations of fracture are generally made, one with reference to shape and the other with reference to texture. For example, mild steel fractures are commonly " cup and cone" in shape and " silky" in texture; hard steel fractures break squarely across—" square break"—and are more or less finely crystalline in texture. Fig. 6 shows the fractures commonly observed in metals and suggested characterizations of the same. Unusual features in the fracture should always be recorded and their causes, if possible, ascertained. For the latter purpose the microscope is a valuable aid.

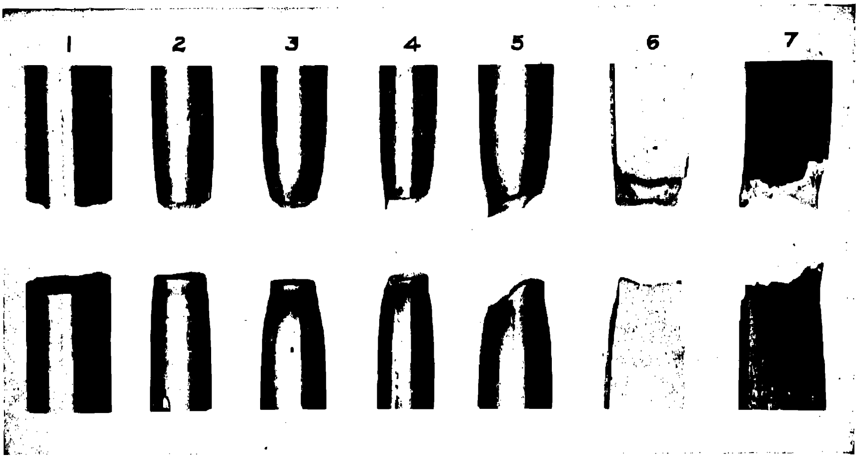

Fig. 6.—Characteristic Fractures of Ferrous Metals in Tension.

(1) Common in cast iron, designated as square break and fine or coarsely crystalline; also in very high carbon steel, texture finely crystalline.

(2) Common to high carbon steel, called fin cup or flat cone with granular to crystalline texture.

(3) Common to soft and medium carbon steels, called full cup and cone with texture silky.

(4) and (5) Common in soft and medium steels (especially when eccentrically loaded), designated as three-quarter cup and cone (4), and half cup and cone (5).

(6) Common in soft and medium steel bars of flat or square section, designated sheared cone with silky texture.

(7) Common in wrought iron, designated jagged and fibrous. (Overheated soft or medium steel may also present a jagged break but not fibrous.)

EXTENSOMETER TENSION TESTS

109. Object.—In addition to the objects mentioned under commercial tension tests, the extensometer test affords a determination of the stress-elongation curve for the material. Consequently the modulus of elasticity, the elastic limit or the limit of proportionality and the resilience may also be measured.

110. Testing.—Specimens like form (*c*) or (*d*), Fig. 3, are preferable for extensometer tests; but it is desirable that the gage length for the apparatus should be at least 8 in. For steels, a specimen fashioned as indicated with a diameter of 0.798 in. (area 0.5 sq. in.), length between shoulders of 9 in. and a gage length of 8 in. is convenient and satisfactory.

To avoid errors arising from the bending of the specimen due to eccentricity in loading, non-homogeneity or initial curvature in the specimen, extensometers provided with three-point contact at each collar are preferable to extensometers of same type having two-point contact. The accuracy of the extensometer should be commensurate with the magnitude of the deformation to be measured. Ordinarily the least reading of the apparatus should be less than one one-hundredth of the deformation at the elastic limit. For steel this requires apparatus reading to 0.0001 in. General requirements for extensometers may be found in Art. 79.

During tests the movable head should be run at low speed, preferably not over 0.02 in. per min. per in. of gage length, and stops made for readings. Vibrations or shocks during loading impair the accuracy of the extensometer readings and should be avoided.

There are two methods of loading which may be used, depending upon the nature of the material and the information desired. If the limit of proportionality is to be determined the load is progressively applied in increments equivalent to about one-tenth of the estimated value of that stress and the corresponding deformations observed. When a stress approximating the limit of proportionality is reached the increments are reduced to about one-tenth of their former value until the yield-point has been passed. Instead of the foregoing method, some prefer to note the loads corresponding to equal increments of deformation until the yield-point is determined. This may readily be done if a self-indicating extensometer is used. It is customary to remove the extensometer from the specimen after passing the yield-point in order to avoid injury to the instrument. Subsequent measurements of elongation may be made with a pair of dividers.

The second method of loading is more often adopted with materials having a curvilinear stress-deformation diagram than with iron or steel. It consists in determining the maximum total deformation and set corresponding to repeated applications of each load. An initial load corresponding to one-twentieth the ultimate strength of the material, or thereabouts, may be applied and removed with determination of accompanying deformation and set. If set occurs the load is repeated and readings of deformation and set taken until the set becomes constant. Then the load is doubled and the same cycle of operations is repeated. This process is applied again and again until the load is reached at which the set continually increases. When this method is applied to a material having a true elastic limit it is well to decrease the increments of load in proximity of the elastic limit.

111. Stress-deformation Diagrams.—It is customary in this country to plot curves using unit stress as ordinates and unit deformations as abscissas with the curve lying in the first quadrant. The scales for such diagrams should be so selected that the slope of the curve will lie between 30 and 70 degrees with the horizontal; otherwise the curvature of the diagram is made too flat or too steep and there is also difficulty in determining the modulus of elasticity with accuracy. If the repetition method of loading has been employed in testing, curves showing the gross sets, gross deformations, and net deformations are generally plotted against unit stress. On such diagrams in addition to a suitable title and proper labeling of the coordinates, it is good practice to indicate the value of the modulus of elasticity beside the line from which it was gotten, to indicate the elastic limit or limit of proportionality, the yield-point, and ultimate strength. The diagram is, in this way, made to furnish the most essential information secured in the test.

COMPRESSION TESTS

112. Objects of Compression Tests.—Whereas tension tests are made for the purpose of determining many of the more significant mechanical properties of materials which are more or less ductile, compression tests are made chiefly to determine resistance to compression and the elastic properties under compression.* In testing materials possessing a high degree of elasticity the elastic limit, yield-point, and modulus of elasticity may be gotten. The determination of the ultimate strength is dependent upon the plasticity of the metal beyond the yield-point. In the softer varieties of steel there is no well-defined point in the loading at which a complete disintegration of structure takes place. From tests of columns made of such materials it appears that the ultimate strength is limited by the elastic limit. Consequently it is quite common to regard the elastic limit as a measure of ultimate strength in compression for these steels.

Materials, possessing a high degree of plasticity, like the minor metals and their alloys, have poorly defined elastic limits and the compressive strength is often based upon the load sustained at a given unit deformation. *These values furnish a basis of comparison but are far from criteria of structural strength unless determined from long-time applications of load.*

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* Herein we shall refer to compression tests as practiced on short prisms. The testing of columns involves consideration of conditions of fabrication, end restraint, form and position of load in addition to the characteristics of the material itself.

For brittle materials like concrete, building tile, stone, brick and timber, the compression test is of most value in establishing criteria of mechanical properties of materials. In tests on these substances, the unit stress at first crack or first sign of failure, at elastic limit—if there is one—and at ultimate are found. The position of the first crack, the character of the explosion at rupture and the shapes of the fragments are all noteworthy. The unit stress at first sign of failure coupled with a knowledge of the place of initial weakening may indicate faulty imposition of load or a local defect in material. The character of the explosion at rupture and the shape of the fragments are also of assistance in determining whether the load was axially or eccentrically applied. Flowing of the bedment often produces vertical splitting of the test-piece.

113. The Form of Compression Specimens.—The form of specimen which has been most frequently adopted is the cube. For materials which rupture on planes inclined more than 45° with the horizontal, the cube is not suitable; since the strength is increased by frictional restraint acting at the surfaces under pressure. Prisms or cylinders with a height equal to twice the least lateral dimension are better types of test-piece for such materials. Owing to weaknesses at corners due to the methods of fashioning the specimen and to the impossibility of securing full resistance from the material in the corners, a cylindrical test-piece is preferable.

In Fig. 7 appears three curves showing the relation of crushing strength to the ratio $\frac{\text{height}}{\text{least lateral dimension}}$. The results on cast-iron cylinders are digested from tests by Mr. Chas. Bouton.* For these tests over 100 specimens were prepared from five bars of each of two kinds of cast iron. Comprehensive tests on Swiss sandstone prisms by Prof. J. Bauschinger † furnished the data for the corresponding curve in the above figure.

From these tests on rectangular prisms, Bauschinger derived the following formula,

$$S_c = 5600 + 1400\frac{\sqrt{A}}{h}$$

in which S_c is in pounds per square inch, A is the area in square inches, and h is the height in inches. For a general formula he recommended

$$S_c = \sqrt{\frac{\sqrt{A}}{\frac{u}{4}}}\left(a + b\frac{\sqrt{A}}{h}\right),$$

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* M.S. Thesis, *Theory and Experiments on Laws of Crushing Strength of Short Prisms*, Washington Univ., 1891.

† *Mittheilungen aus dem Mechanisch Technischen Laboratorium der K. Technischen Hochschule in München*, von J. Bauschinger, Vol. 6, 1876.

where u = perimeter of cross-section; a and b are constants, and the other quantities are the same as before. A simpler relation for Bauschinger's tests on sandstone is given by

$$S_c = 5500 + 1565\frac{d}{h},$$

where d is the minimum lateral dimension.

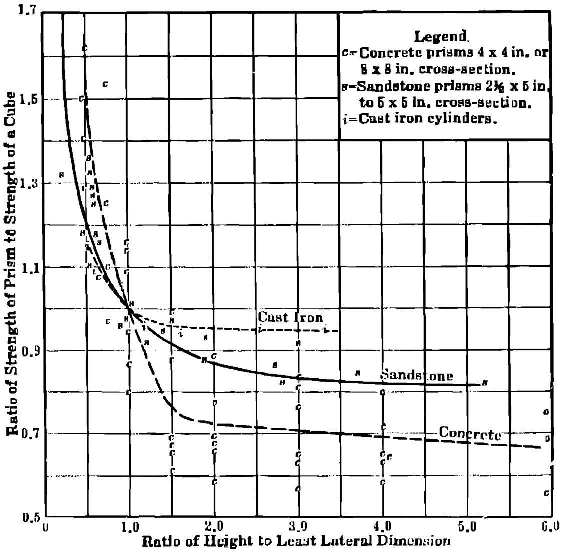

FIG. 7.—Relations between the Crushing Strengths of Prisms and Cubes.

The data for the third curve in Fig. 7 were obtained from 192 tests at several college laboratories in cooperation with the National Association of Cement Users.*

Numerous tests made by H. F. Gonnerman† indicate that the strength of concrete cylinders 28 days old varies with ratio of length to diameter, thus:

Ratio of Length to Diameter...	0.5	1.0	1.25	1.5	2.0	3.0	4.0
Strength Ratio Percentage of 6 by 12-in. cylinder.........	178	115	107	103	100	95	90

From the equation for the curve representing tests on sandstone prisms, Fig. 7, the following relation appears:

$$\frac{\text{Strength of prism}}{\text{Strength of cube}} = 0.788 + 0.222\frac{d}{h}.$$

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* *Concrete-Cement Age*, Vol. 4, p. 141.

† See *Bulletin 16*, Lewis Institute, Chicago, entitled ***Effect of Size and Shape of Test Specimen on Compressive Strength of Concrete.***

From the foregoing it appears that Gonnermann's data on concrete are in fair agreement with Bauschinger's data on sandstone. Hence we may expect a cube of such material to have a strength 15 per cent greater than a cylinder with length twice the diameter.

Best practice in testing ferrous and other hard metals for compressive strength calls for a cylindrical specimen with diameter of 0.798, 1, or 1.125 in. and height of 3 diameters; for modulus of elasticity determinations the diameter should be 1.25 in. and the length 12.5 in. (see *A.S.T.M. Tent. Standards*, Des: E9-33T); and for strength of bearing metals a length of 1 in. and a diameter of 1.25 in. are satisfactory. For concrete specimens a 6 by 12-in. cylinder should be used when the aggregate is less than 2 in. maximum diameter (see Appendix A). For larger aggregate, the cylinder diameter should be half its length and at least four times the maximum diameter of aggregate particle. For mortar either a 2-in. cube or a 2 by 4-in. cylinder is satisfactory. Cubes, because of the mass of existing data and because of relative ease of preparation, are preferred for tests on stone. For wood, 2 by 2 by 8-in. prisms are recommended (A.S.T.M., Des. D143-27).

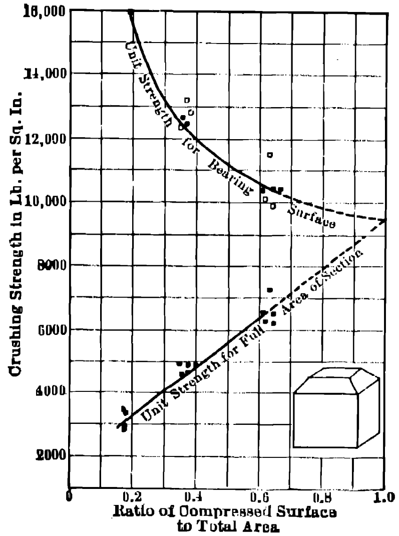


FIG. 8.—Crushing Strengths of Cubes with Chamfered Edges. (Bauschinger.)

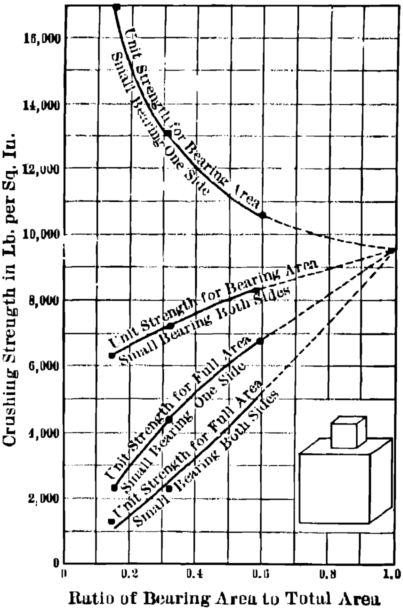


FIG. 9.—Effect of Loading a Portion Only of the Surface of a Cube.

The *modified cube* method makes possible good determinations of crushing strength on portions of concrete beams. Loads are applied to top and bottom surfaces through spherical bearings on opposite square capped areas of the same width as the beam (A.S.T.M., Des. C116-38).

114. Effects of Loading a Portion of the Cross-section.—Tests by Bauschinger on the effect of chamfered edges on the strength of sandstone cubes gave the results shown in Fig. 8. The tests show that material symmetrically disposed outside of the bearing surfaces increases the strength of the test-piece. This increase is less than 3.2 per cent, however, if the bearing area is more than 80 per cent of the gross cross-section.

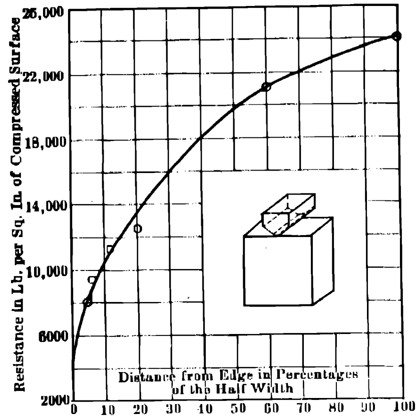


FIG. 10.—Effect of Loading a Zone on the Surface of a Cube. (Bauschinger.)

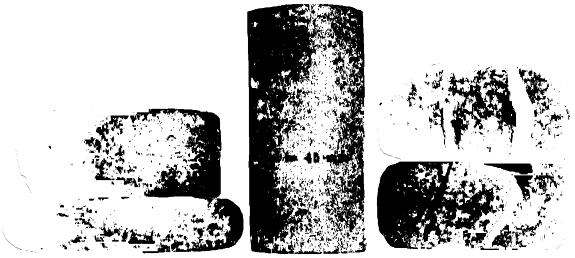
If the pressed surface is square and symmetrically located on a side of a cube the relations of resistances per square inch to the ratio of bearing area over total area are shown in Fig. 9.

The effect of loading a rectangular zone having a width equal to 5 per cent of the side of the cube and a length equal to the side of the cube was also studied by Bauschinger. In this case the resistance per square inch is a function of the distance of the zone from the edge of the surface. The results summarized in Fig. 10 show that the resistance per square inch of bearing area when the center of the bearing area is 4 per cent of width of the cube from the edge is 9500 lb., the normal strength of a cube.

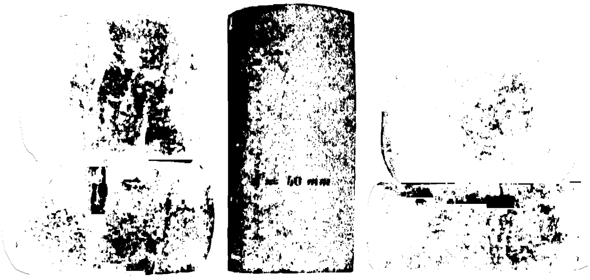
115. Apparatus Required for Compression Tests.—Descriptions of testing machines, bearing blocks, compressometers, and bedments will be found in Ch. II. For tests on the modulus of elasticity the compressometer should be accurate and sensitive to one one-hundredth of the deformation at the elastic limit. It should record deformations on at least two sides of the specimen. The yokes attaching the compressometer to the specimen should be placed not less than half of the diameter of the specimen from the nearer bearing surface. If the yield-point of hard steel is to be gotten, a pair of Capp's multiplying dividers will be found convenient. A spherical seat to permit adjustment due to non-parallelism of the heads of the specimen is especially desirable in testing brittle materials. The value of the seat is small, however, unless provision is made for properly centering the specimens with respect to it.

116. Testing.—The cross-section of the specimen should be determined at several points along its length. On cylindrical specimens measurements on mutually perpendicular diameters should be made. Metals should be measured to one-four-hundredth part and non-metallic materials to one part in two hundred. Building tile, if scored, should be measured outside of the scoring and no allowance made for the area of fillets. Although in specifications for all hollow building block and tile it is customary to demand a minimum strength in terms of the gross section only, it is worth while to obtain the net area in order that the strength of the material itself may be judged.

Great care should be exercised to adjust both the bearing block and specimen so that the line of pressure will pass through the axis of test-piece, bearing block, and testing machine.



Steel Wrought Iron



Wrought Iron Steel

FIG. 11.—Relative Malleability of Wrought Iron and Soft Steel. All the specimens were originally of the shape of the one remaining undeformed. The wrought iron specimens uniformly show large cracks. (From von Tetmajer's *Communications*, Vol. 4, Pl. 5.)

The speed of the movable head of the testing machine ought not to exceed 0.02 in. per minute per inch of height in compressing iron or steel specimens. For plastic and brittle metals, stone, concrete, clay products and wood, speeds should not exceed 0.005 in. per minute per inch of height of test-piece. Where strength only is desired the rate of loading may be made more rapid for loads less than half to three-fourths of the ultimate strength. For very plastic materials a much slower rate of loading should be used if a quantitative determination of the crushing strength is wanted. In any series of tests the method of applying the load should remain constant.

The manner of making compression tests with a compressometer is the same as that outlined in Art. 110. Also, the method of plotting the curve sheet and the information desired may be gotten from Art. 111.

In making a test for crushing strength only, it is well to surround brittle test-pieces with wire meshing to prohibit fragments from flying at rupture.

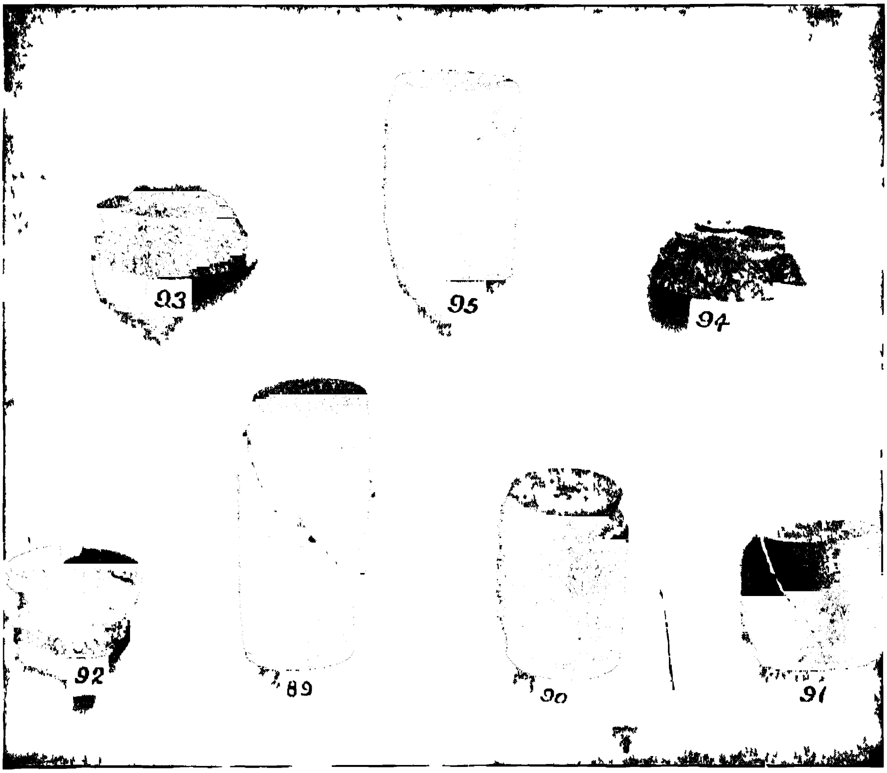


FIG. 12.—Bouton's Compression Tests on Cast Iron.

117. Observations During Test.—Care should be taken to determine the position and character of the first crack together with the load at which it occurs. With materials like low-carbon steel and wrought iron the yield-point will be denoted by the drop of the beam, by the rapid increase in motion of the divider pointers, and—in rolled material—by scaling. In tests of brittle materials the shape of the fracture should be stated thus: "pyramidal," "plane inclined θ degrees to horizontal," or "cone"; and the texture of the broken surfaces examined and reported. Characteristic fractures of wrought iron, cast-iron and sandstone speci-

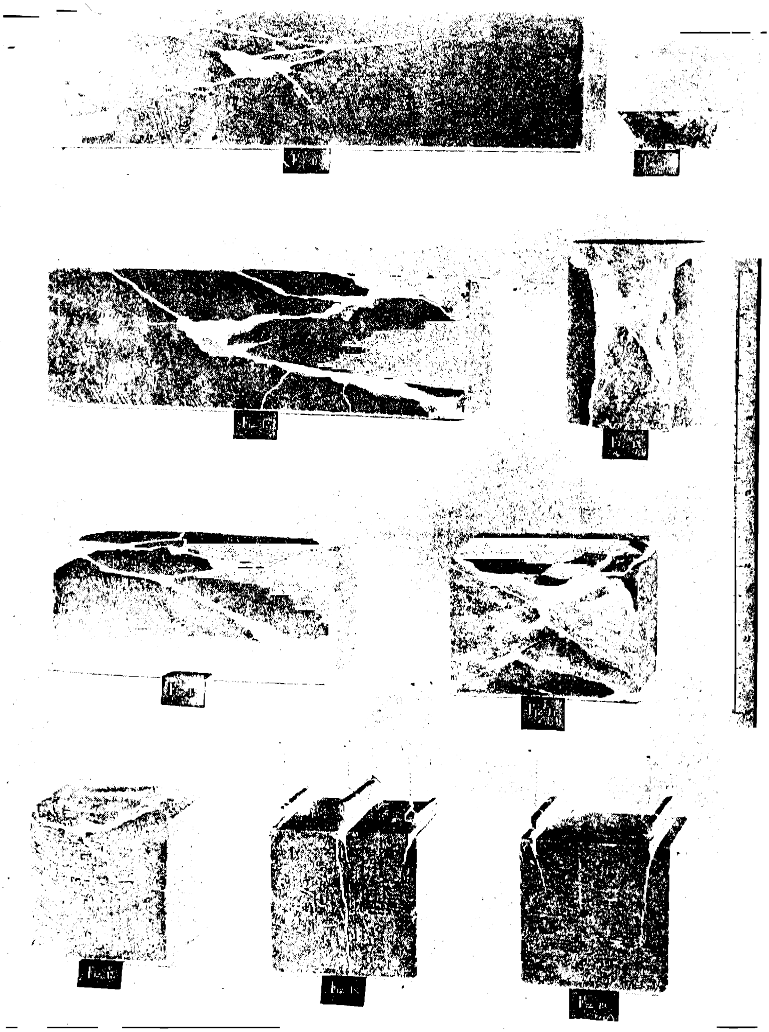


FIG. 13.—Bauschinger's Compression Tests on Sandstone.

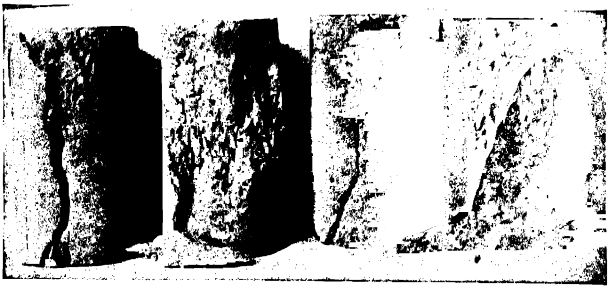


FIG. 14.—Typical Failures of 6×12-inch Concrete Cylinders.

mens may be found in Figs. 11, 12 and 13, respectively. Typical fractures of concrete cylinders appear in Fig. 14.

TRANSVERSE TESTS

118. Objects of Transverse Tests.—For determining ultimate strength, elastic limit, yield-point, resilience and modulus of elasticity of brittle materials in cross-bending, the transverse test is often used. This test is of especial value in determining the strength, stiffness, and toughness of brittle materials. Since the deflections of brittle specimens are many times larger than the elongation in tension tests, a much more accurate determination of resilience and energy of rupture can be made in the transverse test without expensive apparatus for measuring deformations. Furthermore, both the machine and the specimen required are inexpensive and the test may be rapidly made.

Cast-iron, brick, stone, and concrete are tested principally for strength, sometimes the resilience and modulus of elasticity are obtained. Timber is tested for its strength, stiffness and resilience. Springs and spring-steel are tested for elastic limit, deflection under given loads, and resilience. Railroad rails are sometimes tested for elastic limit and ultimate strength. I-beams and other structural shapes used as beams are also tested to determine constants for use in design. Transverse tests are also made for scientific purposes to test the correctness of the ordinary flexure formulæ for strength and deflection.

In most cases transverse tests of ductile materials are not so well adapted to determine quality as tensile tests. Furthermore, the modulus of rupture and transverse elastic limit of such materials vary greatly with the length of span.

Since three kinds of stress, tension, compression, and shearing, are developed when a beam is bent under the action of external forces, the problem is more complex than those thus far considered. Usually the shearing stresses are left out of account in designing both for strength and stiffness, but the conditions under which this stress should be recognized and taken account of are given in Art. 28 for strength, and Art. 30 for deflection.

119. Specimens for Transverse Tests.—As Fig. 15 shows, the modulus of rupture of gray cast iron is more variable for 12-in. spans than for longer spans. Such evidence led the A.S.T.M. to adopt in 1929 a vertically cast cylindrical specimen 1.20 in. in diameter at mid-length and 21 in. long. Specimens are tested under a center load over an 18-in. span. By using a cylindrical specimen a uniform thickness of skin is insured and shrinkage strains due to corners are obviated.

For transverse tests of malleable cast iron either a rectangular specimen 1 in. wide and $\frac{1}{2}$ in. thick or a cylindrical test-piece $\frac{3}{4}$ in. in diameter tested with center load over a 12-in. span is satisfactory. If the material has a good ductility, rupture will not occur in such test.

When tests are made to determine constants for I-beams, T-bars or similar sections, it is necessary that the specimen be geometrically similar (preferably of the same size to avoid differences due to rolling) to the section under investigation. Tests showing the variation in the transverse strength properties of cast-iron specimens, due to changing the shape and thickness but not the area of cross-section, appear in Table 1.

For plate glass and flat springs, test-pieces should be flat with a length ten or more times the depth. For timber, rectangular specimens are best. The Forest Products Laboratory uses 2 by 2 by 30-in. specimens with a 28-in. span for small beam tests. In tests of larger timber beams the span should be 15 or 20 times the depth. For cement and mortar specimens 1 by 1 by 6-in. prisms with a 5-in. span, and for concrete 6 by 6-in., or 8 by 6-in., beams with an 18-in. span, are convenient.

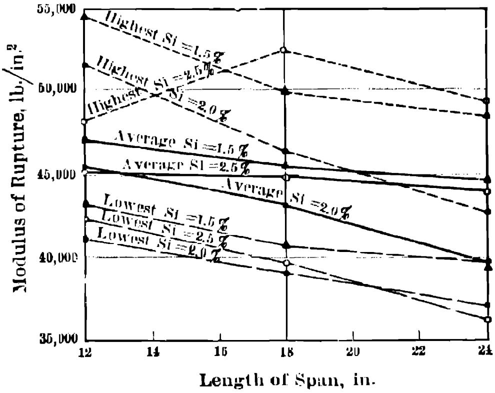


FIG. 15.—Relation of Span to Modulus of Rupture for Cast-iron Arbitration Test. Bars Differing in Silicon Content. Each Average Represents Nine Tests. (Matthews, in *Proc. A.S.T.M.*, Vol. 10, p. 303.)

120. Apparatus Required for Transverse Test.—Descriptions and general considerations of apparatus are found in Ch. II. The testing machine should have a capacity two to four times the estimated strength of the specimen. If used, a deflectometer should be accurate and sensitive to 1/100 of the deflection at the elastic limit, if E is to be measured, and to 1/100 the maximum deflection for determinations of the latter. For measuring fiber strain, deformeters should be accurate and sensitive to 1/100, or less, of the strain in the gaged length at the elastic limit. Wherever possible one should avoid fastening deformeters close to concentrated loads.*

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* For further data see *Bulletin* No. 84, Engr. Expt. Sta., Univ. of Wis., on ***Influence of Form and Scale on Strength***, by R. J. Roark, R. S. Hartenberg, and R. Z. Williams.

TABLE 1.—THE EFFECT OF SHAPE ON THE TRANSVERSE STRENGTH OF CAST IRON

(C. H. Benjamin in *Machinery*, May, 1906)

Beams loaded at center over an 18-inch span

No. of Results Averaged.	SECTION.			Breaking Load, P (lb.).	Modulus of Rupture, $S_m = \frac{4.5Pc}{I}$, (lb./in.^{2}).	Modulus of Elasticity, in 1,000,000 lb./in.^{2}
	Shape.	Area (in.^{2}).	$\frac{I}{c}$* (in.^{3}).			
2		4.42	1.31	7,375	25,270	8.28
2		4.44	1.55	8,125	23,450	9.25
2		4.58	3.12	16,150	23,210	6.61
2		4.40	2.88	19,900	31,125	7.05
2		4.36	3.38	21,400	28,450	5.61
2		4.41	3.22	25,250	35,300	6.49†
2		4.38	5.11	28,175	24,840	4.41
2		4.56	5.78	24,250	19,400	4.54
2		4.84	6.46	31,550	22,010	5.62
2		4.61	6.52	31,750	21,940	4.71
2		4.88	6.48	34,625	24,060	4.84
1		4.51	0.81	5,400	30,000	10.74
1		5.10	1.99	8,350	18,900	8.57
1		4.61	0.69	4,700	30,580	10.17
1		4.80	1.61	8,800	24,600	11.06
1		4.41	0.83	4,400	23,700	
1		4.60	2.30	12,250	24,000	9.34
1		4.47	1.77	7,900	20,050	7.10
1		5.02	4.36	22,600	23,250	7.88
1		4.50	1.78	10,200	25,800	6.23
1		5.18	5.95	25,000	18,900	7.28

* c is the distance to the extreme fiber in tension. † Only one result.

Rocker supports or swinging links should be used at the ends of the specimen to prevent longitudinal compression in the lower fibers when the beam is loaded. Also, if a pair of loads is imposed through a loading beam, rollers should be used between specimen and loading beam to avoid compounding of the specimen and loading beam through friction at the load points. A high intensity of compression under the loads and over the reaction should be avoided by the use of metal bearing plates.

For transmitting loads to large timber beams, the Forest Products Laboratory uses heavy maple shoes which rest upon $\frac{1}{8}$-in. steel plates. The lower surface of each shoe is cut to a circular arc having a chord length of $13\frac{1}{2}$ in. and a mid-ordinate of $\frac{9}{16}$ in.

When structural shapes are tested, they should be braced and loaded as far as possible, in accordance with the conditions of use. I-beams and girders should, in most cases, be laterally braced at the supports.

For tests of cast and brittle metals, the speed of moving head should not exceed 0.1 in. per minute. The Forest Products Laboratory uses a speed of $\frac{1}{4}$ in. per minute on large timber beams and 0.1 in. per minute on 2 by 2 by 30 in. specimens. For tests on brick, concrete, stone, and similar brittle materials the rate of stressing the extreme fiber should be nearly constant as the maximum load is approached. In that vicinity suitable limiting rates are 500 to 1,000 lb. per sq. in. per min.* In the tests where deflections are being read, it is best to apply the load at a sufficiently low rate to permit the readings being taken without stopping the machine. When deformeters are being used the time intervals allowed for readings should be constant during such tests.

It is well to use increments of load of about one-tenth the estimated load at elastic limit and when in the proximity of the elastic limit reduce the increments to one-fifth of their former value.

121. Observations During Test.—The transverse elastic limit of metals as determined from deflections is generally higher than the tensile elastic limit and not so plainly perceived. The yield-point is denoted by the drop of beam and by scaling in the case of rolled sections. The position of the scaling and its advance over the test-piece are well worth careful note. The ultimate strength of ductile metal specimens is often very hard to determine with exactness; but, if a slow speed is used, the maximum load may be approximately ascertained.

In testing brittle materials like cast iron, the observer must be alert if he is to note the load and deflection at failure. The character of the fracture should be recorded with care.

When testing timber, concrete, malleable cast iron and like substances, the load at first crack should be noted and the position and character of the crack recorded.

122. Load Deflection Curves.—Ordinarily, loads are plotted as ordinates and deflections as abscissas. The scales should be such that the initial portion of the curve has a slope of over 20 degrees with respect to the load axis. On such diagrams it is good form to indicate the elastic limit, yield-point, modulus of rupture (S_m), modulus of elasticity, and resilience.

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* Formulæ for speed of the moving head of the testing machine appear in Art. 231.

IMPACT TESTS

123. Objects of Impact Tests.—Inasmuch as the effect of speed of loading on the toughness of materials has not been well determined, it has been the practice to use data from impact tests for estimating resistance to shocks or blows. On the other hand, owing to the impossibility of accurately measuring the proportion of the energy of a blow which is absorbed by a specimen, and owing to the influence of form of specimen and other factors, the results of impact tests do not furnish absolute indications of shock resistance. Nevertheless, by carefully standardizing machines, specimens, and the methods of testing, with respect to service conditions, it is possible from impact test data to make comparisons valued by the designer.

Transverse impact tests have long been used to determine the shock resistance of structural elements like rails, axles, car wheels, and car couplers, also for measuring shock resistance of brittle materials like wood or cast iron. In tests of such structural parts, acceptance is usually based on the capacity of selected pieces to withstand an arbitrary number of blows with a limited deformation. In tests of brittle materials the energy of rupture and type of fracture indicate the quality. (For methods of testing wood see *A.S.T.M. Standards*, Des.: 143–27.)

When transverse impact tests are used to test ductile materials, it is necessary to groove the specimen to obtain rupture. Thus high concentrations of stress are caused at the groove, which make the test results purely qualitative. Users of this test claim that it serves well in comparing the abilities of similar materials to serve in the form of intricate and severely stressed parts in correlating the effect of heat treatments of steel and of heat-treated forgings with service (see *A.S.T.M. Tent. Stds.*, Des.: E23–34T).

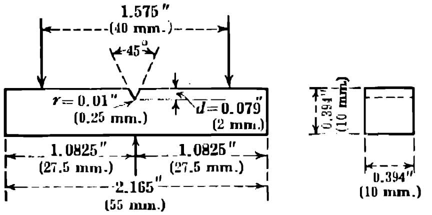
Tensile and compressive impact tests have been little used to date. Difficulties in providing axial loading of specimens have militated against usage on brittle materials. For ductile materials, since small eccentricities of loading have little effect on the energy of rupture, tensile impact tests are far more accurate than notched-bar transverse tests. The applications of this test are deserving of much more attention than they have thus far received. (See Symposium on Impact Testing, *Proc. A.S.T.M.*, 1938.)

124. Specimens for Impact Tests.—For brittle castings, bars similar to those recommended for transverse static tests are well adapted for transverse impact specimens. If service parts are to be used as cast, the skin should not be removed from specimens.

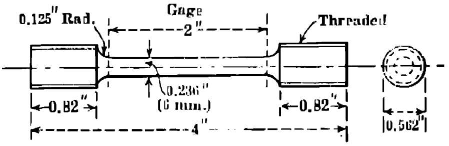
In transverse tests on ductile structural parts it is well to mark a number of equal intervals on both sides of the part where heavy stresses will occur to permit strain measurements after testing.

For transverse impact specimens of ductile materials, a great variety of specimens notched at mid-length have been proposed. In order to make satisfactory comparisons the size of the specimen and the type of notch should be standardized. Since defects have a more marked effect on small specimens they are usually preferable to large specimens.

The A.S.T.M. Committee E-1 in 1926 recommended the specimens shown in accompanying figure. Concerning the notch, Fremont (*Proc. A.S.T.M.*, 6th Congress, 42) showed that slight variations in width of saw slot were not important. Thomas (*Proc. A.S.T.M.*, Vol. 15, p. 63) showed that the angle between the sides of the notch may be varied from 0 to 30 deg. without material effect. Tetmajer, however, found that the curvature at the bottom of the notch should be maintained constant. Depth of notch must also be held constant.



Specimen for Transverse Impact Tests of Ductile Metals.



Specimen for Tensile Impact Tests of Ductile Metals.

For tensile impact tests of metals the specimen shown above is recommended. Punch marks placed on the shoulders permit elongation measurements after failure.

125. Considerations Involved in the Selection of an Impact Testing Machine.—The fundamental conditions which one must consider in selecting an impact machine have been briefly considered in Art. 58. It must be pointed out, however, that machines are far from being standardized. In the drop machines, with the exception of the machine for testing rails (see Art. 60), there is a wide diversity of conditions. No standard relations of tup to anvil have been adopted, nor has there been any standardization of the height of drop. Fremont recommends a drop of at least 4 meters and an anvil weighing forty times as much as the tup. Experience seems to show that the hammer should be at least fifteen times as heavy as the specimen. When drop machines are used to apply blows smaller than required for rupture, some means should be provided to avoid secondary effects on the test-piece due to rebounding of the hammer.

The Charpy pendulum machine has been adopted by the German Association for Testing Materials, and recommended by A.S.T.M. (see Des.: E23-34T), but there are in use a large number of other types, in some of which the anvil is much too light. In such machines the loss of energy through vibration must be great. The cantilever method of supporting a specimen should be avoided, since it is very difficult to duplicate the end conditions in successive tests.

Mann's tests (Art. 59) indicate that many metals tested in impact tension exhibit constant energies of rupture for velocities below a certain critical value, termed the transition velocity, and for higher velocities they show a marked reduction in toughness. This fact should be given due consideration in all impact test programs and should receive proper attention in design. Friction effects in drop machines may be made small by freeing the guides of rust and wiping them with powdered graphite. Calibrations for friction losses can be made by measuring the elastic deflection of a spring attached to the anvil of the machine when subjected to different impacts and comparing the energy absorbed with that required to deflect the spring a like amount under static loading. The friction in drop machines equipped with a drum and tuning fork may be got by comparing the slope of the velocity-time graph with the acceleration due to gravity.

The curvature of the knife-edges on the anvil and especially on the hammer is of importance. The hammer knife-edge on the Charpy machine has a radius of curvature of 2 mm.

126. Testing.—In drop machines where successive blows are to be struck, provision should be made to keep the specimen from jumping off the supports during the test by means of slots or yokes near the ends; but fixing of the ends should be avoided. In tests on pendulum machines, the specimen must be placed tightly against the anvil. Where rupture is produced by a single blow it is best to adopt a uniform height of drop in order that the velocity of impact may be the same in all tests.

Pains should always be taken to see that every specimen is so placed that it receives the blow in the same position as its predecessors. Nicked specimens must be placed with the nick exactly opposite the hammer knife-edge. If such specimens are round, the base of the nick should be parallel to the hammer knife-edge when the latter is in contact with the test-piece. Timber specimens should be struck normal to the annual rings.

The elastic limit is found by subjecting the specimen to progressively increased blows and plotting the energy of each blow against the square of the corresponding deflection. The elastic limit is the unit stress corresponding to the point at which the square of the deflection increases in faster ratio than the energy. In such tests it is impossible to measure the total energy absorbed by the specimen. The amount lies between the energy of the final blow and the sum of the energies in all the blows. In general, it is not possible to prescribe which of these qualities will form the better index for comparing ultimate resistance to impact, unless the forms of the load-deflection curves are known. Consequently, a single blow large enough to produce rupture is the preferable method of securing data on energy of rupture under impact.*

127. Observation after Rupture.—In tests on metals, the shape of the fractured surface, its inclination with respect to axis of the piece, and its texture should all be recorded. If the metal is ductile the relation of the plane of failure with respect to the notch or nick should also be carefully observed. When a rolled piece is tested the limits of the scaled area are noteworthy. On polished specimens, the area showing lines of strain and the character of these lines should be noted. Microscopic examinations of the portion next to the break are often very useful in determining structural defects which cause peculiar results.

HARDNESS TESTS

128. Kinds of Hardness.—Hardness as applied to metals, minerals and other solids is a term of variable meaning. Resistance to abrasion, to indentation, and to cutting have all been considered criteria of hardness; but no one of these serves in general, as a criterion for the others. Apparently abrasive resistance depends largely upon adhesion between the particles, resistance to indentation upon cohesion and cutting resistance upon both cohesion and adhesion. Therefore, it seems likely, and the results of tests † show, that for pure metals which are nearly homogeneous these different resistances are closely related. However for substances like cast iron, tempered steels, alloy steels, and alloys in which there is a decided difference in the mechanical properties of the constituent particles there appears to be no relation between these resistances. Since in practice distinct demands for the different sorts of hardness exist, it is quite desirable to standardize tests for the measurement of these properties. Thus far no single test has been devised which is in general well-adapted to measure all of these different kinds of hardness; nor is it likely that one ever will be devised. Relative hardness of similar substances may be gotten but no absolute standard appears.

129. Types of Hardness Tests.—The scratch test made with a diamond point is the oldest and simplest method of determining abrasive hardness. However, owing to difficulties in standardizing, this test has not come into general use. Probably 'the most satisfactory method of using it is that of Martens (see Art. 61).

For measuring cutting hardness, especially of cast iron, use has been made of the Bauer drill test. In this test the quantity of metal removed by a standard drill operating under constant speed and pressure for a certain time interval, is considered an index of cutting hardness.

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* For methods of testing axles and rails under impact consult the current *Standards* of the A.S.T.M.; also see *Engr. News*, Vol. 75, p. 701.

† See T. Turner's tests, *Jour. of Iron and Steel Institute*, 1909, No. 1, p. 426.

Resistance to penetration has been the usual criterion for hardness of metals. The weighted pyramidal punch dropped from various heights was early standardized by Martel.* He concluded that the energy (*D*) required to displace unit volume of a given material is independent of the shape of the pyramid, the weight, or height of fall, and, hence, *D* is a suitable index of resistance to penetration for that material.

In most indentation testers the load is statically applied, and the penetrator is a sphere or is provided with a rounded tip to avoid the variations due to wear. The modern Vickers hardness tester, which utilizes a diamond-pointed pyramid, is an exception. With Herbert's pendulum hardness tester two different tests of hardness can be made, which, it is claimed, provide criteria of resistance to indentation, to cutting, and to flow. Detailed consideration of the three widely used indentation tests, the Brinell, the Rockwell, and the Shore scleroscope (Art. 62 and 63), follows.

130. Objects of Indentation Tests on Metals.—Indentation tests serve two very useful purposes: (1) to determine the quality or conditions of parts which—on account of size or shape—cannot be subjected to other mechanical tests or which must not be destroyed in testing; (2) to determine hardness. In either case comparisons must be made with materials of like nature, since none of these tests furnishes a satisfactory indication of the comparative hardness or other mechanical properties of all substances.

131. Relationships between Resistance to Indentation and Strength.—In an excellent analysis of the Brinell test, R. H. Heyer (*Proc. A.S.T.M.*, Vol. 37, Pt. 1, p. 119) shows that the sink-in types of hardness impression arise from relatively large underlying shear strains and the ridging type comes from relatively large surface compressions. Hence sink-in types usually connote a relative weakness in shear whereas the ridging type indicate a high ratio of shear to compressive yield strength. From such evidence Heyer gave ratios for the shear yield strength in terms of the tensile or compressive yield strength for three classes of alloys which had been subjected to different amounts of work hardening.

Several investigators † have found a rough linear relationship between the ultimate strength and hardness of steels. Unfortunately the equations for this relationship do not agree in all cases. Petrenko ‡ in tests on a wide variety of steels calculated the tensile strength (S_t), in pounds per square inch, from $S_t = 515B$ for values of Brinell hardness (B) less than 175. For Brinell hardness above 175 he used $S_t = 490B$. His equations for Rockwell hardness values follow.

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* The device was first used by Col. T. J. Rodman (U.S.A.) before 1860; see his *Report of Experiments on Metals for Cannon and Cannon-Powder*, 1861. For standardization, see *Commission des Méthodes d'Essai des Matériaux de Construction*, Vol. 3, p. 261.

† See Turner in *Jour. Iron and Steel Institute*, 1909; Abbott in *Proc. A.S.T.M.*, Vol 15, p. 43; Unwin in *Inst. of Mech. Engrs.*, 1918, p. 422.

‡ Technologic Paper No. 334; U. S. Bureau of Standards.

For the B-scale using a $\frac{1}{16}$-in. ball and a 100-kg. load (R_B),

$$S_t = \frac{3,750,000}{130 - R_B} \text{ for } R_B < 90$$

$$S_t = \frac{3,570,000}{130 - R_B} \text{ for } R_B > 90 < 100.$$

For the C-scale using the diamond cone and a 150-kg. load (R_c),

$$S_t = \frac{730,000,000}{(100 - R_c)^2} \text{ for } R_c < 10$$

$$S_t = \frac{695,000,000}{(100 - R_c)^2} \text{ for } R_c > 10 < 40;$$

and

$$S_t = \frac{12,250,000}{100 - R_c} \text{ for } R_c > 40.$$

In all but a few cases Petrenko's calculated strengths were within 10 per cent of the experimental tensile strengths.

For non-ferrous metals Petrenko's tests failed to disclose any relationship between tensile strength and hardness.

132. Applications of Indentation Tests.—Among the more important applications of indentation tests are the following: 1, to determine rapidly the carbon content of iron and steel parts; 2, to determine strength in parts which cannot be subjected to regular strength tests; 3, to test the uniformity and degree of tempering or hardening in steels; 4, to test the effect of cold working of steels; 5, to ascertain the condition of finished parts without injury.

133. A Comparison of the Brinell, Scleroscope, and Rockwell Methods.—In general, the Brinell test is less rapid, requires a larger surface for test, produces a more pronounced disfiguration of the part tested, penetrates to a greater depth and integrates the resistance of a larger number of particles than does the scleroscope or the Rockwell device. The chief error in the Brinell method arises in measuring the diameter of the impression. The error is due to the upward flow of metal around the sphere and the elastic deformation of the ball. This trouble is obviated by employing Devries' method of determining the depth of the impression, see Art. 62.

On the other hand, it appears that the scleroscope indications are affected by properties of the specimen other than hardness as the results tabulated below show. Furthermore, the readings of the scleroscope

Material.	Plate Glass.	Ivory.	Cork.	Hemlock.	Hard Steel 0.70% C.	Soft Steel 0.14% C.	Lead.
Scleroscope Reading	116	45	37	31	23	12	12

are influenced by the method of holding the specimen, by the smoothness of the surface, by the rigidity of the support on which the specimen rests, by the shape of the hammer point, and also by the size of the indentation. The scleroscope tests conditions existing less than 0.01 in. from the surface.

Both the scleroscope and the Rockwell device may be used to test materials of any hardness. The Rockwell test is also rapidly made. Its readings are very consistent and there is less chance of error due to maladjustment of apparatus or personal equation of operator than in tests with the scleroscope. The method of measuring the depth of indentation is superior to that commonly employed in Brinell tests. Although the indentations made by the Rockwell machine are usually deeper than those made by the scleroscope, they are not as marked as in Brinell tests. If desired, the disfigurations due to Rockwell tests may be made still less by the use of loads lighter than the standard. The fact that this machine has two standard scales, and a number of others more or less used, is a slight disadvantage in comparing materials which have marked differences in hardness. This objection is offset by the refinements in measurement thus obtained.

Petrenko found for a wide range of ferrous and non-ferrous metals that the Brinell number (B) may be estimated within 10 per cent from a Rockwell number by the following semi-empirical equations:

$$B=\frac{7300}{130-R_B} \text{ for } R_B \text{ between 35 and 100;}$$

$$B=\frac{1,420,000}{(100-R_c)^2} \text{ for } R_c \text{ between } -20 \text{ and 40}$$

$$B=\frac{25,000}{100-R_c} \text{ for } R_c \text{ above 40}$$

$$B=\frac{3710}{130-R'_B} \text{ for } R'_B \text{ between 0 and 120.}$$

Here R'_B signifies Rockwell reading for a $\frac{1}{8}$-in. ball under a 100-kg. load and other symbols have their previous meanings.

134. Testing by the Brinell Method.—The surface to be tested should be plane, free from scale, and smooth; it need not be polished. The balls should be made of hardened steel or other suitable material.* They should not suffer a permanent deformation greater than 0.0001 in. when loaded with 3000 kg. against a steel piece having a hardness of 500 or greater. The balls should measure within 0.0025 mm. (0.0001 in.) of 10 mm. (0.3937 in.). Balls should be remeasured after every test in which the hardness exceeds No. 500.

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* See *A.S.T.M. Standards*, Des.: E10–27.

The standard load for the ferrous metals is 3000 kilograms (6614 lb.); for the minor metals and alloys, 500 kilograms is often used. Pressure should be applied slowly and kept on the specimen for thirty seconds. The distance between the center of the indentation and the edge of the surface should equal at least 2.5 times the diameter of the impression. In no case should the side of a specimen exhibit a bulge after testing when compared with a straight edge. The thickness of the specimen should be at least ten times the depth of the indentation.*

For tests on small or very thin specimens it is necessary to use a smaller ball than the standard. For such tests the applied load should be varied in proportion to the square of the diameter of the ball (D) in millimeters. Thus for iron and steel the load $P=3000\frac{D^2}{10^2}$ or $30D^2$ kilograms. For brass, bronze, and other soft metals $P=5D^2$.

If the depth of penetration is measured by Devries' method, a microscopic reading to 0.001 mm. should be employed. If the diameter of the impression is desired, measurements should be made to at least 0.01 mm. on two mutually perpendicular diameters.

The general equation for Brinell's numbers is

$$H=\frac{P}{\frac{\pi D}{2}(D-\sqrt{D^2-d^2})},$$

where H = hardness; P = pressure; D = diameter of ball; and d = diameter of impression.

In terms of the depth of impression, t, the equation is $H=\frac{P}{\pi D t}$.

135. Testing with the Scleroscope.—The surface of the specimen should be horizontal. If the specimen is soft, a fine file is sufficient to smooth the surface; but if a hard steel is to be tested the surface should be ground on the side of a fine emery wheel. In tests on very hard metal, it may be advisable to polish the surface. In any event care should be taken to avoid injury through overheating. Mill scale, blisters or decarbonized products of annealing must be removed before testing.

When parts are standardized by this test it is necessary that each should be held in the same manner. Since the rebound of the hammer is largely affected by the rigidity of the test-piece, all small pieces should be securely held. A vise can be employed in most cases, but for pieces of peculiar shape a jig or plaster cast may be more suitable.

The apparatus must be held in a vertical position. For ease in reading, the light should be directed downward toward the scale so that the top of the hammer glistens. An estimation of the rebound of the hammer should be made before the test and the eye, held about 20 in. from the apparatus, should be sighted slightly below the calculated scale reading. For accurate reading of small differences in rebound, the magnifier may be set after the range has been obtained.

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* See H. Moore, *Proc. I.A.T.M.*, 1909, 2₄.

Always avoid testing the piece twice in the same spot. Surfaces composed of widely varying constituents should be tested at several points to secure the range in rebound.

136. Testing with the Rockwell Machine.—Prior to running a test, the machine should be equipped with the proper penetrator and tested several times on the standardized block provided by the makers. Tests should be made on one side of the block only, thus avoiding bearing troubles from indentations. After the surface has been covered with indentations the block should be discarded. The surface of the specimen should be smooth and normal to the axis of the penetrator. The specimen should rest solidly on the anvil. Care should be exercised to see that the specimen is properly forced against the penetrator and the dial turned to set mark. The time of applying the major load may be regulated to some extent by adjusting the dash pot, but it should not be made less than 4 sec. Whenever a reading above 100 is obtained on the B-scale, a check should be made on the standard block. Erratic readings also should always be followed by check readings on the standard block. The diamond cones must be handled with care and should not be subjected to shock during loading of specimens. (See *A.S.T.M. Stds.*, Des.: E18–36.)

SHEAR TESTS

137. Essential Conditions in Transverse Shear Tests.—In order to obtain the true shearing strength of any substance it is necessary to develop in it, along a given plane, shearing stress only, unaccompanied by the bending stresses of tension and compression. To accomplish this it is necessary to concentrate the external forces of action and reaction on planes an infinitely small distance (*dx*) apart. Any finite distance between these planes will develop a cross-bending action and its resultant direct stresses across the plane of shear. As it is impossible so to concentrate the external shearing forces, it is necessary to overcome the bending stresses due to non-concurrence of the external forces by preventing the bending of the specimen subjected to these forces. This is done by reinforcing the specimen between the shearing planes or by grooving the specimen in the planes of shear and supporting it by auxiliary clamps.*

138. Objects of Transverse Shear Tests.—Although shear stress is present in nearly all cases where cross-bending exists, it becomes of practical importance in only a limited number of instances. In the design of riveted joints, bridge pins, crank-pins, short I-beams, and wooden beams especially, the shear stress must be considered. It is therefore of importance to be able to determine roughly at least, the shear strength of certain metals and of timber. It is, however, impracticable in the transverse shear test to determine the elastic limit or modulus of elasticity. These determinations on metals can be gotten best from torsion tests.

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* Both Dr. Kennedy and Mr. Barba grooved their specimens for double shear, and also held them in rigid forms. See Rep. French Commission, Vol. 3, Plate 19.

139. Specimens for Shear Tests.—For shear tests of metals, specimens of rectangular cross-section with a breadth equal to at least four times the depth are satisfactory for use with a Johnson shear tool. If round specimens are used, this shear tool should be modified so that the specimen is clamped in a circular die.

Wooden specimens cut in accordance with Fig. 14. Ch. II, are satisfactory for use in the simple shear tool shown in the same figure. In preparing such specimens, one should remember that timber is weakest in longitudinal shear on planes tangent to the annual rings.

140. Testing.—To avoid bending, it is necessary that the clamps on the shear tool should grip the specimen tightly. Care must also be taken to place the specimen in the axis of the shear tool with the shear planes at right angles to the axis of the test-piece. To avoid eccentric loading of the specimen, it is necessary to apply pressure to the shear tool through a crossed knife-edge or through a spherical seat.

The speed of applying the load should not exceed 0.05 in. per minute for metals and not over 0.1 in. per minute for wood.

In addition to the ultimate load, observations of the shape of the fracture and its texture should be made.

TORSION TESTS

141. Objects.—In general, torsional shear stress may be produced without bending, nevertheless one must not forget that on certain planes in a body under torsion these shear stresses combine to produce tensile or compressive stresses of equal intensity to the shear stresses. A torsion test differs from a transverse shear test in that the deformation acts over any predetermined length of the bar, and in that it varies from zero at the center of the bar to a maximum at some point on the outside. By using hollow cylindrical specimens having a large internal radius compared to thickness, it is possible to determine the ultimate shear strength of many materials. If, however, the tensile strength of the material is less than its shear strength, failure in tension will result from combined shear stresses.

For elastic materials, the elastic limit, yield-point, torsional modulus of rupture, modulus of elasticity and torsional resilience may be obtained provided a cylindrical test-piece is used. Torsion tests are made not only on shafting but also on variously shaped members of machines or structures which are subjected to twisting couples. In the latter tests the twisting moment at the yield-point, the ultimate and the angle of twist at the yield-point and ultimate are the criteria of most use in design.

142. Specimens for Torsion Tests.—For tests on torsional properties of materials, the round bar (either hollow or solid) is the only satisfactory form of specimen. Since it is possible to multiply the twist of the specimen by using radial arms of considerable length, it is not important in tests on the modulus of elasticity that a long gage length be used. Ten inches is generally ample. If the test is to be carried to rupture, it is well to have the portions at the grips about 20 per cent larger in diameter than the gage portion. The transition, however, from the enlarged ends to the gage portion should be made by fillets of large radius.

When it is desirable to determine the torsional strength and ductility of structural elements having non-circular cross-sections, the test-piece should be geometrically similar in form to the shape under consideration. It should also be remembered that in such sections the maximum shearing stress is produced at points on the periphery nearest the axis. Formulæ for maximum intensity of stress in elliptical and rectangular sections are given in Art. 23.

143. Testing.—Descriptions of several machines and types of detrusion apparatus are given in Ch. II. The detrusion indicator should be accurate and sensitive to one one-hundredth of the estimated angle of twist in the gage length at the elastic limit. The machine should be so constructed that end tension is not exerted on the specimen. In testing wire, means for making the end tension constant should be provided. Care must be exerted in gripping to insure against slipping. If the specimen is hard and has cylindrical ends, it is well to cut fine closely spaced grooves along elements of the surface to afford a grip for the teeth of the jaws.

The cross-section of the specimen should be measured to one part in one thousand at several points along the gage length; and, to afford a rough determination of the angle of twist, a fine line may be scribed along a longitudinal element of the surface. If the modulus of the elasticity is to be determined, it is well to secure about ten readings of twist within the elastic limit and to cut down the increments about 80 per cent when the twisting moment becomes 90 per cent of the estimated moment at the elastic limit. The speed of the twisting head within the elastic limit ought not exceed 0.005 revolution per minute per inch of length of specimen. Beyond the elastic limit this speed may be greatly increased.

At the yield-point scaling will be observed on rolled sections. The location and the spreading of the scaling is of special note in tests on non-cylindrical shapes. At failure, the texture of the fracture and the inclination and shape of the fractured surface should be observed. As a measure of torsional ductility, the angle of twist per unit of length may also be determined.

BEND TESTS OF METALS

144. Significance of Bend Tests.—A rough but very valuable test of the ductility of malleable metals is afforded by the various types of bend test commonly practiced in the shop. The test consists in sharply bending a bar or portion of a structural shape and noting the angle at which rupture occurs on the convex surface of the bend. If the material can be bent through an angle of 180° without rupture it is considered to have exhibited a high degree of ductility. The test is also used to ascertain the effects of certain shop operations—punching, drilling, and shearing—on ductility. Fig. 16 shows results of bend tests on wrought iron and steel specimens. This test is a more severe measure of ductility than the tension test but has not been so carefully standardized. The greatest advantage of the test is that it may be made without expensive equipment, consequently methods of standardizing should not remove it beyond the range of ordinary shop appliances.

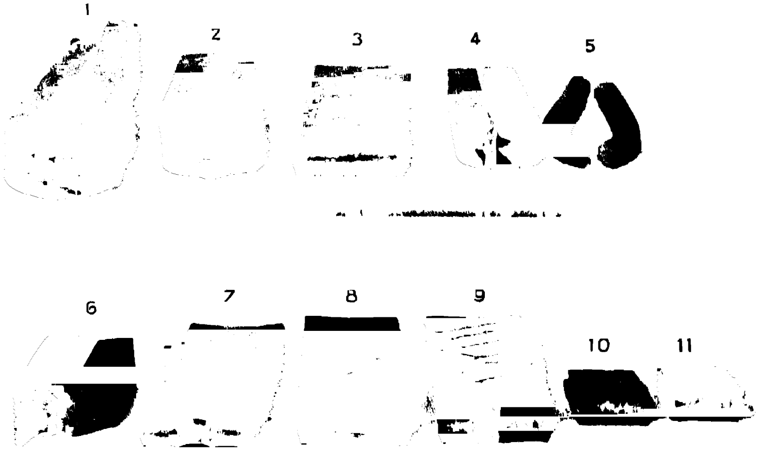

FIG. 16. Results of Cold Bend Tests. (1) ¾×1-in. Wrought Iron Bar, Note Crack; (2) ¾×1-in. Mild Steel Bar, (3) ¼×2-in. Mild Steel Flat; (4) ⅝×⅝-in. Cold Rolled Bar; (5) ½-in. 0.90% Carbon Steel Rod, (6) ¾×1-in. Wrought-Iron Bar Nicked and Bent, Note Crystals at Left, (7) Mild Steel Flat Punched and Bent with Die Side Outside, Note Cracks, (8) Mild Steel Flat Punched and Bent with Die Side Inside, (9) Mild Steel Flat Drilled and Bent; (10) Mild Steel Flat Sheared along Edges and Bent with Die Side Inside; (11) Mild Steel Flat Sheared along Edges and Bent with Die Side Outside, Note Cracks.

145. Various Kinds of Bend Tests.—Cold-bend, quench-bend, hot-bend and nick-bend tests are all used more or less. Of these the cold-bend test is most commonly practiced. This test is ordinarily made at normal shop temperatures; sometimes to test ductility at low temperatures, specimens are artificially cooled. Cold-bend tests are made on structural steel for bridges, buildings, ships, locomotives, reinforced concrete, rivets, splice bars and on the various grades of wrought iron. The test, as commonly made, measures ductility of the metal at normal temperatures only.

For determining ductility of metal parts subjected to alternations of high and low temperatures, use is sometimes made of the quench-bend test. The specimen is first heated to a yellow heat and suddenly cooled by plunging in water at a temperature of about 80° F. It is then subjected to the bend test. Boiler-rivet steel is often subjected to this test.

To measure the ductility of wrought iron at welding heat, a hot-bend test is sometimes specified. The specimen is heated to a temperature of 1700 or 1800° F. and immediately bent. This test is useful in detecting a high-sulphur content.

Nick-bend tests are made on wrought iron to determine structure. The A.S.T.M.* requirement for the nick-bend test of engine-bolt iron follows: "The test specimen, when nicked 25 per cent around with a tool having a 60-degree cutting edge, to a depth of not less than 8 nor more than 16 per cent of the diameter of the specimen, and broken slowly shall show clean fibers, free from crystallization."

146. Specimens for Bend Tests.—The cross-section of specimens for bend tests may be round, square or rectangular; finished shapes are sometimes tested. Rods and bolt stock are generally tested without machining. When specimens are sheared from plates the edges should be planed and the corners rounded with a file. If this is not done, cracks may start at the corners due to weakening of the metal by the shearing process. Martens advocated that the length of flats should be eighteen times the thickness, the breadth three times the thickness, and the radii of the sheared corners should be one-fourth of the thickness.†

If the specimen is nicked it is preferable to use a planer or milling machine rather than the cold chisel, although the latter method is the easiest. Martens recommended that the depth of the groove be between 10 and 20 per cent of the thickness of the test-piece. It should extend across the surface which is under tension during the test.

For bend tests on perforated specimens the hole should be located in the center of the test-piece. It should be punched before the specimen is sheared from the plate. The diameter of the hole should bear a fixed relation to the thickness of the test-piece. Martens recommended that the diameter of the hole should be twice the thickness and the width of the test-piece should be five times its thickness.

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* See *A.S.T.M. Standards*, Des.: A84–36.

† *Handbook of Testing Materials*, p. 319; also *A.S.T.M. Tent. Std.*, Des.: E16–38T.

147. Various Methods of Testing.—Methods of starting and closing the bend vary considerably, and herein is the one of the main causes for discrepancies in this test. On small specimens it is possible to use a blacksmith's sledge and anvil. However, such practice is not recommended. When elongation measurements on the convex side of the bend are to be made, the specimen is lightly marked at intervals of 0.1 in. throughout the middle third of its length. The middle third of the specimen is then clamped in a vise and the end portions suitably bent with a hammer. The specimen is then subjected to axial compression in a vise, press, or testing machine and bending continued until failure of the outer fibers occurs, or until the maximum requirement has been fulfilled. In applying the load the speed may be as rapid as can be controlled but shock must be avoided. The elongation of the outer fibers in a length of 0.3 in. for specimens $\frac{1}{4}$ to $\frac{1}{2}$ in. thick and in 1 in. for thicker specimens can then be made with a flexible tape, making allowance for width of any included cracks (see *A.S.T.M. Tent. Std.*, Des.: E16–38T).

Bending attachments (see Art. 54 and 55) yield concordant results and are recommended when numerous tests are to be made.

When nicked or perforated specimens are tested, the test-piece should be so placed that the bend will occur at the minimum cross-section. In testing punched specimens the die side should be subjected to tension in the bend test.

148. Influence of Thickness of Specimen.—If we consider that the neutral plane remains in the center of the test-piece during bending, the per cent elongation of the outer fiber is $100\,\frac{t}{2R}$, where t is the thickness and R the radius of curvature of the neutral surface. Tests show that although the above assumption is erroneous, the elongation of the outer fiber does vary directly with the thickness and inversely with the radius of curvature. Consequently, it is customary in specifications to increase the radius of curvature for thick test-pieces. Thin steel plates are commonly bent flat through 180° (roughly $R=t$); those above $\frac{3}{4}$ in. are bent about a pin having a diameter equal to the thickness of the plate. It is common practice to bend rods about pins of equal diameter. (For examples see specifications for various classes of steel and wrought iron in the current *A.S.T.M. Standards*.)

149. Observations during Tests.—Owing to the congestion of metal on the concave side of the bend and restricted lateral expansion, the neutral axis of the specimen must approach nearer to the concave side as the angle of bend increases. Also, more of the specimen is severely stressed and deformed as the bend angle increases. Consequently the angle through which the specimen is bent without cracking forms a crude index of ductility. It is good practice in tests for comparative purposes to observe both the angle at first crack and at rupture. To make such measurements with accuracy the use of a cylindrical plug gage or a cone graduated on one element will be found convenient. Most American specifications omit elongation measurements and are so worded that no observations are required until the specimen has been bent a prescribed maximum amount.

THE VALUE OF MECHANICAL TESTS

150. A Résumé of the Utility of the Principal Mechanical Tests.—In the following paragraphs appear a brief summary of the properties revealed by the various mechanical tests and the principal uses now made of these tests for ascertaining the quality of materials.

Tension Tests.—With ductile materials the elastic and ultimate strengths, ductility, elastic resilience, toughness, modulus of elasticity, and an estimate of the composition and homogeneity can be had. Without an extensometer the test is not so informative for brittle materials; but it is effectively used to reveal strength and homogeneity.

Tensile tests are inexpensive and the most informative of the mechanical tests for ductile metals, rubber, fabrics, cloth, paper, and yarn. With brittle materials, they are much used to test cements and cast iron.

Compression Tests.—With ductile materials the yield point or yield strength, elastic resilience, and a poor measure of toughness can be obtained. Usually, with brittle materials, only the strength and uniformity are ascertained. If a compressometer is used, the modulus of elasticity can be found.

Compression tests are used principally to test the strength of brittle materials like wood, concrete, brick, stone, and cast iron.

Transverse Tests.—With ductile materials the yield-point and modulus of elasticity can be found. With brittle materials the strength, measured by modulus of rupture, the flexibility, toughness, modulus of elasticity, and an estimate of the composition and homogeneity can be obtained.

This test is the most informative and inexpensive of the mechanical tests for brittle materials like cast iron, wood, brick, cement, and concrete.

Bend Tests.—Cold, hot, quench, and nick-bend tests are sometimes used. The first three of these tests are measures of ductility for metals subjected to the respective conditions. Cold-bend tests detect very high carbon contents in steels normally cooled; they may detect brittleness due to a high phosphorus content or improper treatment in working or rolling. Failure in the hot-bend test may be due to a high sulphur content. Failure in the quench-bend test is likely to result if the carbon content is above 0.20 per cent. The nick-bend test is useful in determining the structure of the metal and to detect imperfect methods of manufacture.

These tests afford a simple, inexpensive, and valuable means for the shopman to determine the suitability of ductile metal like boiler plate, fire-box steel, reinforcing bars, rivet metal, engine-bolt iron, and stay-bolt iron.

Hardness Tests.—The resistance of metals and other materials to indentation is the form of hardness most often tested. The Brinell ball apparatus, the Rockwell machine, and the Shore scleroscope are the devices most used for the determination of this form of hardness. The Brinell test permanently deforms the specimen but is a better index of hardness (within the limits of the hardness of the ball) than the scleroscope test. The scleroscope indications are influenced by other factors than resistance to indentation, but the apparatus may be used on harder material than the Brinell device and does not seriously alter the surface of the specimen. The Rockwell test combines the advantages of both the Brinell and scleroscope tests, but it does somewhat more injury to the surface tested than the scleroscope.

The indentation tests afford an inexpensive and very valuable means for determining the quality of hardened and tempered metals, for standardizing the hardness of parts, and for detecting flaws in parts which on account of peculiarity in form can not be subjected to other mechanical tests.

Impact Tests.—Transverse impact tests afford a valuable measure of shock resistance for brittle materials. If the shock resistance of ductile metals is desired, the tensile impact test is more informative. If transverse impact tests are made on ductile metals a notched specimen is generally necessary.

The test is most used for cast iron and wood, and for structural parts like rails, axles, shafting and forgings.

Shear Tests.—The transverse shear test affords an imperfect measure, due to the existence of bending stresses, of shearing strength.

These tests are used somewhat for metals, wood and for riveted and nailed joints.

Torsion Tests.—A measure of strength (the computed twisting strength), ductility, and toughness in torsion is afforded by this test. The shearing modulus of elasticity may be gotten if a proper torsion indicator is used.

The test is occasionally used on ductile metals, shafts and parts which are to be subjected to twisting.

CHAPTER IV

CHARACTERISTICS, PHYSICAL PROPERTIES, AND USES OF WOOD

151. The Timber Situation.—The original stands of timber in the United States are estimated to have contained 5200 billion board feet of timber. Much of this timber has been consumed, and much of it was destroyed to make way for agriculture. There remains, however, over 600 million acres of forest land on which, according to the best estimates, there is a stand of 1,668 billion board feet of saw timber in merchantable sizes, and some 970 million cords of small timber and cordwood.

The depletion of virgin forests without proper consideration of future reproduction has naturally resulted in a shifting of production centers and changes in species dominating the market. The principal centers of softwood production at the present time are the Southern and the Pacific Coast states, with southern yellow pine and Douglas fir, respectively, as the principal structural species. More specifically, about two-fifths of the present lumber cut is produced in each of these regions.

Extensive studies are being inaugurated to appraise the present forest situation with respect to future requirements. Whereas present consumption greatly exceeds the annual growth, it is evident that second growth is becoming an important factor in augmenting the supply. With the practice of forestry on land unsuited to other crops, and with efficient timber utilization, the United States can reasonably be expected to meet its future needs, at least after an initial adjustment period.

Although the per capita consumption of lumber in the United States has decreased sharply since 1905, the decline in total lumber consumption has been less. One of the most significant causes of reduced per capita consumption is more economical use resulting from a better knowledge of the properties of wood, and the more extensive application of wood preservatives.

For structural uses, timber of excellent quality is still readily available. Better utilization of structural timber may be assured by the application of the improved grading rules, which have been adopted by the various organizations, including A.S.T.M. and A.R.E.A., and by the use of the working stresses and design formulæ recommended by the Forest Products Laboratory. Significant trends having a far-reaching effect on utilization are the development of improved joints, through the medium of metal connectors, and the growth of the plywood industry.

Engineers are concerned principally with uses of timber for structural purposes. Each year they direct the use of pine, hemlock, Douglas fir, cypress, oak, redwood, chestnut, ash, spruce, and cedar aggregating a value of perhaps an hundred million dollars. Consequently it is quite necessary that they should be well informed concerning the properties and uses of this very valuable building material, in order that they, too, may use it to best advantage and conserve it wherever possible.

GENERAL CHARACTERISTICS OF WOOD *

152. Structure and Appearance.—Although color, weight, smell, and resonance are often helpful, the structure of wood is the only reliable means of identifying species. Structure is closely related to all the mechanical properties of wood and very often furnishes an explanation for observed differences in these properties. Furthermore, structure and color determine the beauty of wood, as seen in the hard pine ceiling, the quartered-oak desk, the "bird's-eye" maple dresser, the mahogany paneling, and many other examples of decorative woodwork. For the engineer a knowledge of structure is of most importance because of the relation of structure to species and mechanical properties. We shall, therefore, briefly consider the different classes of timber and certain of their more prominent structural characteristics before taking up their properties.

153. Classes of Trees.—Two classes of trees furnish practically all of the structural timber of the United States. They are the gymnosperms (naked seed-leaved trees), of which the conifers are the important family; and the dicotyledons (trees having two seed leaves), which are commonly termed broad-leaved trees. A third class, the monocotyledons, of which the yuccas and palms are the more prominent native members, are used to a small extent in some of the Southern States.

Sometimes trees are also classified by the way that they shed their foliage. The conifers which are of most importance in the lumber industry are evergreen, although the larch and bald cypress shed their needles annually. On the other hand nearly all of the broad-leaved trees are deciduous in our northern latitudes.

Frequently, in the trade, the lumber of broad-leaved trees is called hardwood, and that of the conifers softwood. Here again the terms are inexact; since poplar, basswood, and horse-chestnut (broad-leaved trees) are soft woods, while longleaf pine and yew (conifers) are hardwoods.

The classes of conifers which are of most importance structurally are pine, fir, hemlock, cypress, spruce, redwood and cedar. Oak, maple, red gum, poplar, chestnut, birch, beech, basswood, elm, ash and hickory are much-used broad-leaved trees.

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* In preparing this chapter reference was made to *Bulletin No. 10* of the U. S. Forestry Div. by F. Roth, to *Economic Woods of the United States*, and *Mechanical Properties of Wood*, by S. J. Record, and to *Wood Handbook*, U. S. Dept. of Agriculture.

Both conifers and broad-leaved trees grow in diameter as well as in height through the addition of yearly layers of wood, each of which forms immediately under the bark. On the other hand, the yuccas and palms increase principally in height. Although alike in manner of growth, conifers and broad-leaved trees differ markedly in structural detail and in character of wood elements. The wood of the conifers is characterized by a marked likeness in the wood elements and in their arrangement, while the wood of the broad-leaved trees consists of a greater variety of fibers and cells which lack the regular arrangement seen in the conifers.

154. Structure of Wood in General.—If one examines a sawn log of well-grown structural timber, he will perceive a small pith at the center of the cross-section surrounded by numerous concentric rings of wood which are, in turn, encircled by the bark. The concentric rings represent the layers of wood added each year during the life of tree. These *annual rings*, therefore, furnish valuable information regarding the age of the log, the rapidity and the uniformity of its growth. The thickness of the annual rings will be found to vary greatly in different trees of the same species and in different parts of the same cross-section. Trees grown in the open or after a forest has been cleared (second growth) exhibit wider rings than those which grow more slowly in the forest. Generally the rings are widest at the center and become narrower nearer the bark. Also the width of the same ring will vary from the bottom to the top of the tree. It is widest at the bottom in young thrifty trees, but in the old trees of the forest it is widest near the top. In thrifty forest trees the center rings are often a half inch or more in width, but in stunted specimens rings less than one-two-hundreth of an inch wide are found. With the conifers a medium rate of growth is conducive to high strength and toughness; whereas a rapid growth is desirable to produce maximum toughness and strength in hardwoods like hickory.

Closer observance of a single annual ring discloses that it is not uniform in composition. In many of the conifers the interior of the ring is decidedly lighter in color than the outer portion; the exact opposite is true in the case of the oaks, while in a cross-section of hard maple no great variation in the color of a single ring is visible to the naked eye. These differences in color are due largely to variations in the size and structure of the wood cells and fibers. In the *non-porous* conifers the color of the earlier wood is due principally to cells which are less compact than those grown more slowly in the summer (Fig. 1). This difference in color and ring structure is not, however, very pronounced in white pine. The *ring-porous* woods like the oaks and the hickories owe the darker color of their early wood to the presence of numerous pores, each of which is large enough to admit a pin point, and which are almost absent in the later wood (Fig. 2). *Diffuse-porous* woods, like beech and maple (Fig. 3), show little variation in the appearance of the early and late wood because of the more uniform dispersion of the pores across the ring. Owing to the time of growth in our climate, the early wood is called *spring wood,* and the later wood is termed *summer wood.*

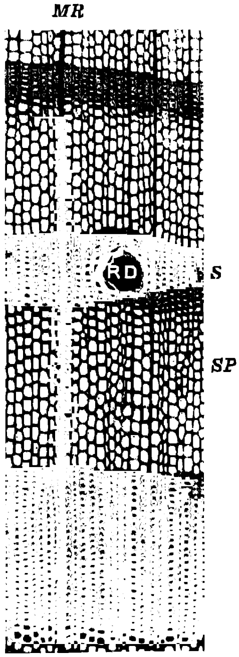

FIG. 1.

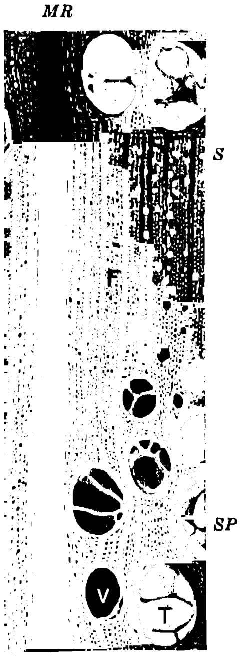

FIG. 2.

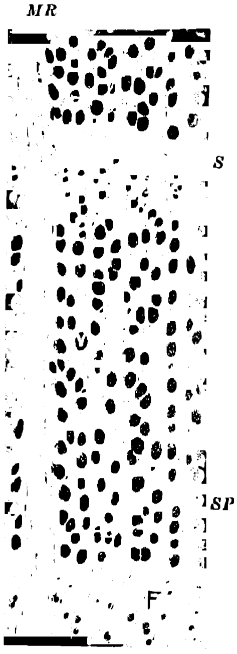

FIG. 3.

FIG. 1.—Cross-section of Longleaf Pine, a Nonporous Wood. (Note absence of pores; resin duct, *RD*; thick cell walls in summer wood, *S*; thin walls in spring wood, *SP*; narrow medullary ray, *MR*.)

FIG. 2.—Cross-section of White Oak, a Ring Porous Wood. (Note large vessels, *V*, in spring wood, *SP*, some being clogged with tyloses, *T*; broad medullary ray, *MR*; also fibers, *F*.)

FIG. 3.—Cross-section of Beech, a Diffuse Porous Wood. (Note the uniform disperpersion of vessels, *V*; fibers, *F*; medullary ray, *MR*.)

[Figs. 1, 2, and 3 are magnified about 27 diameters. Reduced from photomicrographs prepared by the Forest Products Laboratory, Forest Service, U. S. Dept. of Agric.]

Since the summer wood is denser, harder and stronger than the spring wood, it follows that the percentage of summer wood in a stick of timber affords information concerning the mechanical properties of it. (See Art. 238.) Furthermore, the contrast between the spring and summer woods is sometimes of assistance in distinguishing different timbers of the same class—the pines for example.

The characteristic appearance of the annual rings after the log has been sawn into boards is seen in Figs. 4 and 5. Two important differences will at once be noted in these figures. The more open spring wood of the pine board is lighter colored than the denser summer wood, whereas in the oak the porous spring wood makes it appear darker than the more compact summer wood. Also, on the transverse section of the oak there are well-marked radial bands or *rays* which appear as light-colored parallel lines on the radial section. These rays, often termed *medullary rays*, are quite pronounced in many of the hardwoods but are less easily observed by the eye in the softwoods. They are, however, present in both classes of trees and serve as distributors of water and food supplies between the bark and adjacent layers of wood. In the oaks the rays lend the beauty to the grain of the quarter-sawed lumber. In all classes of timber they greatly influence shrinkage and thereby affect mechanical properties, as we shall see later.

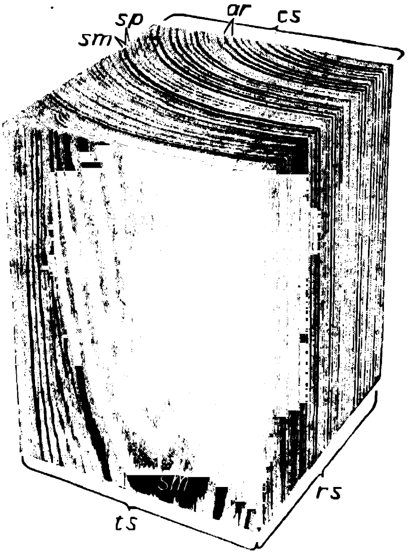

Fig. 4.—Board of Pine. *cs*, cross-section; *rs*, radial section; *ts*, tangential section; *sm*, summer wood; *sp*, spring wood; *ar*, annual ring.

As a tree grows the cells near the pith gradually become inactive so far as the life of the tree is concerned. They do not decay, however, but remain a firm and strong support to the tree. This inner lifeless portion of the trunk is called the *heartwood*. The *sapwood* is the surrounding envelope, between the heartwood and the bark, which carries the water and alternately stores and supplies the food for the growing portions of the tree. Generally, through the infiltration of pigments, the heartwood is darker in color than the sapwood, although the contrast is not always marked. Red cedar, redwood, yew, tamarack, elm and birch exhibit a strong contrast in the color of the sapwood and heartwood; but in fir, hemlock and spruce the contrast is largely wanting.

The proportion of sapwood varies considerably in various parts of the same tree. Generally the envelope of sapwood becomes thinner near the top of the tree and in the limbs. Very thrifty rapid-growing trees generally have a larger proportion of sapwood than trees of like species having a stunted growth, but the latter often have more rings in the sapwood.

The width of sapwood varies considerably for different kinds of wood; it is small for longleaf pine, white pine and chestnut, and great for loblolly pine, Norway pine, ash, maple, hickory and gum. Occupying the peripheral portion of the log the sapwood always forms a large proportion of its mass.

In old tree trunks the sapwood is likely to be weaker, freer from knots, and more susceptible to decay than the heartwood. In comparatively young timber the difference in strength between heartwood and sapwood is small. Sapwood is more readily impregnated with preservatives than heartwood. Some claim that the sapwood of hickory is stronger and tougher than the heartwood, but tests by the Forest Service * have failed to substantiate this prejudice.

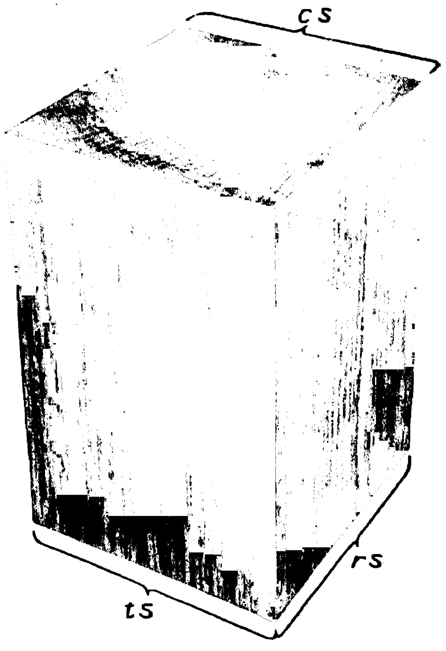

Fig. 5.—Board of Oak. *cs*, cross-section; *rs*, radial section; *ts*, tangential section; *r*, medullary rays.

155. The Grain of Wood.—The comparative width of annual rings, the direction and the arrangement of the cells and fibers are the causes of the *grain* of the wood. Thus trees of rapid growth having wide annual rings produce coarse-grained wood, while those of slower growth produce wood with narrow rings or fine grain. When the wood elements are straight and run parallel to the pith the wood is said to be straight-grained. When the wood elements do not run parallel to the axis of the piece, it is said to be *cross-grained*. This includes *spiral, diagonal, interlocked* (succeeding layers winding in opposite direction), *wavy, dip* (one wave only), and *curly* grain.

The slope of the grain can be ascertained by noting the direction of the surface checks, resin ducts and annual layers. Direction of grain can usually be told by observing the spreading of a drop of ink along the grain. Cross-grain has a pronounced weakening effect on the strength of beams when the slope is 1 : 15 or greater.

156. Defects in Timber.—Besides irregularities in the character of the grain, there are, from a structural standpoint, three important classes of defects in timber—knots, checks and shakes.

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* *Bulletin* No. 80, p. 50; also see Art. 239.

Knots are the beginnings of branches which have been surrounded by the parent stem. Generally the piths of branch and stem join and the annual rings of the branch are continuous with the lower rings in the stem.

The size of a knot, unless otherwise specified, is measured by the average of the maximum and minimum diameters on the surface of a piece. *Pin knots* are under ½ in. in diameter, *small knots* are from ½ in. to ¾ in., *medium knots* from ¾ to 1½ in., and *large knots* are over 1½ in. in diameter. *Round knots* are oval or circular in form. When a knot is exposed by sawing lengthwise it is called a *spike knot.* *Sound knots* are as solid and hard as the surrounding wood. A *decayed* knot contains advanced decay and is softer than the surrounding wood. In an *encased knot* the annual rings fail to grow into the fibers of the surrounding wood. A *tight knot* is so securely fastened that it will hold its position in the finished piece. When the wood fibers deflect around one knot it is called a *single knot*; when they deflect about two or more knots as a unit, the group is called a *knot cluster.* Two or more knots radiating from a common center are termed *branch knots.*

Knots greatly affect the workability, cleavability, shrinkage, and the strength of wood. (Art. 240.) Knots in the coniferous boards are likely to be filled with resin, a condition which renders them difficult to cover with paint.

A *check* is a longitudinal crack which is usually normal to the annual rings.

A *shake* is a longitudinal crack usually between the annual rings of growth.

Both shakes and checks adversely affect the durability of timber because they readily admit moisture and air. If present near the neutral plane of a beam they may materially weaken its resistance to horizontal shear.

157. Color and Odor.—The colors exhibited by different woods or by the sapwood and heartwood of the same tree are due to chemical compounds impregnating the wood substance. Freshly formed wood is nearly colorless, while the sapwood is lighter than the heartwood in all species having any pronounced demarkation between the two. Exposure to air deepens the color of wood and immersion under water darkens it very materially. When wood is attacked by fungi it loses its luster and becomes dull in appearance.

Color, together with structure, is an important determinator of the beauty of mahogany, cherry, black walnut, red gum and sycamore. In many woods the color of the heartwood is a valuable aid to identification. Thus the white of the white spruce, the yellow of the osage orange, the yellow-brown of the tamarack, the light brown of the chestnut, white oak and sycamore, the red-brown of the red oak, red cedar and red gum, and the dark brown of the black walnut are all distinctive marks.

Odor is also due to chemical compounds in the wood substance. It is much reduced by exposure to the weather but can generally be determined by making a fresh incision in the wood. Heartwood gives a stronger odor than sapwood. Odor is undesirable in woods which are to be used as food containers. In cedar chests, however, it forms a protective against moths. As a means of identification the resinous odor of longleaf pine, the aromatic odor of cedar, the sour smell of oaks, the smell of kerosene emitted by catalpa are noteworthy. Decayed timber often has a smell which is pronouncedly different from the odor of the sound wood; decaying red oak for example smells like heliotrope.

PHYSICAL PROPERTIES OF WOOD

158. Density and Specific Weight.—The true specific gravity of all wood substance is approximately 1.55; whereas the specific weight and *apparent* specific gravity (ratio of weight of given block to weight of an equal volume of water) vary with the density of the wood. Herein the term specific gravity will indicate the *apparent* value which varies from 0.11 for balsa wood to 1.29 for black ironwood. This criterion conforms with our conceptions of heavy and light wood and the degree of its buoyancy in water.

The percentage of moisture in the wood has a very large effect upon the specific weight. Thus green wood is heavier than dry wood, the green sapwood of a given log is generally heavier than the accompanying heartwood, and the wood of the green sapling is heavier than that from the old tree. Since the moisture content greatly influences the specific weight, true comparisons of this important property can only be made on dry specimens.

Considering dry wood, we may say that the wood of a given tree is heaviest in the lower portion of the trunk, lighter in the limbs and branches and lightest in the roots. The heaviest timber in old pine is found about half way between the center and the bark, where a medium rate of growth has obtained. In young pines and in ring-porous woods like oak the heaviest wood is at the center of the stump. In general the dry heartwood is much heavier than the dry sapwood. The dry wood of the oak sapling is heavier than that of the old tree, but in the pines and spruces the reverse is true. In the conifers high density is favored by a medium or slow rate of growth and a high percentage of summer wood. Thus the specific weight of shortleaf pine, redwood, western hemlock and Douglas fir has been found to vary linearly with the per cent of summer wood.* In the ring-porous woods like oak, chestnut, and elm a rapid rate of growth is attended by the production of a large proportion of thick-walled fibers, thus causing a high specific gravity; but in the diffuse porous woods like maple, birch and beech, where the cell structure within the rings is more homogeneous, no relation between rate of growth and density is apparent. As in coniferous timber, however, so in wood from broad-leaved trees, the density increases with the proportion of summer wood.

Since the specific weight of dry wood is often a very important criterion of the strength and other mechanical properties of timber (see Art. 236), it is well worth determining. In the laboratory small discs about 1 in. thick are cut from different portions of large sticks so that the variation in weight and moisture content may be represented. The pieces are then carefully weighed, dried in an oven to constant weight at 100° C., and again weighed. The specific weight is then computed from the volume and dry weight of the disc. Density is frequently based upon the volume at test and the oven-dry weight. In the field a rough but satisfactory method of determining density is afforded by boring holes of known diameter and depth in different portions of a timber and determining the specific weight from the dry weight of the shavings and the volume of the hole.

The range in average values for the specific gravity and specific weight of the more important native timbers are given in the table opposite. All data were obtained from small clear specimens from the top 4 ft. of 16-foot butt logs of typical trees. Other results are given in Table 1, Ch. VI. It will be understood that individual specimens may vary considerably from the values tabulated.

A practical rule for estimating the effect of small changes in moisture content, less than 6 per cent, in air-dry wood (12 per cent m. c.) is to allow a change of 0.5 per cent in the specific weight for a change of 1 per cent in the moisture content.

159. Moisture in Wood.—Water is found in three portions of wood: (1) it constitutes over 90 per cent of the protoplasm in the living cells; (2) it saturates the cell walls; and (3) it fills, more or less completely, the pores of the lifeless cells. It occurs in all three portions of the sapwood but only saturates the cell walls in the heartwood. In the sapwood of white pine, containing 100 per cent of water (in terms of the dry weight of the wood) about 5 per cent of the water is found in the living cells, 35 per cent in the cell walls and the remaining 60 per cent in the empty cells.† The water in the cells of the sapwood is drawn upward into the leaves of the tree and converted into sap. The sap is conducted down through the bark and provides nourishment for the wood forming immediately beneath the bark (the *cambium*). The water in the sapwood con-

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* See Fig. 17, *Bull.* No. 108, Forest Service.

† Roth in *Bull.* No. 10.

161. Shrinkage and Its Effects.—For purposes of illustration consider a very small, thin transverse section of green wood, Fig. 7*A*. If this section is very slowly and uniformly dried no change will be noted in the disc until the water in the pores is evaporated. Then the cell-walls will gradually become thinner and the sides of the disc *ab*, *bd*, etc., will shorten. No contraction in length of the disc is, however, observable. Furthermore, since the thickness of the end walls of the cells or fibers is very small compared to their length, it is apparent that longitudinal shrinkage of a thicker disc composing several fiber lengths will be negligible. If we repeat the experiment with a disc like that of Fig. 7*B*, we will observe that the side *ab* shortens more than *cd* and that the surfaces *ab* and *cd* are curved, Fig. 7*C*. In other words, thick-walled cells shrink more than those having thin walls. We shall, therefore, find that a curved disc of wood one annual ring in width will straighten in drying owing to the fact that the thick-walled cells of summer wood shrink more than the thinner walled cells of spring wood. This inequality in shrinkage between the various cells produces stresses of a serious nature during the drying of timber.

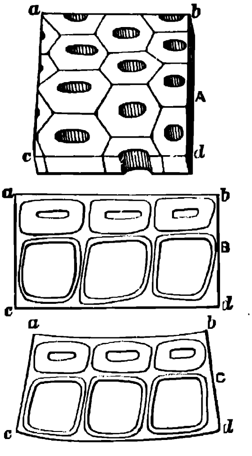

Fig. 7.—Warping of Wood.

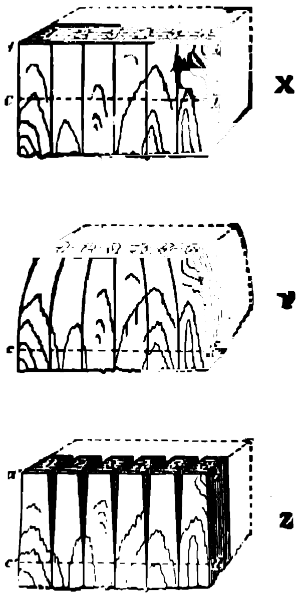

Fig. 8.—Formation of Checks.

Again, if a stream of warm air is directed against the side *cd* of the moistened disc, Fig. 7*A*, it will be noted that it shortens much more rapidly than *ab*, owing to the more rapid evaporation of moisture. When [illegible] of the disc are equally dry, *ab* and *cd* are again of equal length

Thus a partially dried board exposed to the sun's rays becomes concave on the upper side, but may be straightened by turning the board over and allowing the moisture in the convex surface to be evaporated.

Since water is evaporated more rapidly from the ends of the wood elements than from the sides, a piece of wood like that in Fig. 8*X* will shrink more laterally at *ab* than at *cd*. This action produces bending in the piece as shown in Fig. 8*Y*. If the rapidity of drying is sufficiently great, the resulting pull across the grain of the wood will exceed its tensile strength and checking ensues, Fig. 8*Z*. After the piece has completely dried many of these checks close, although the weakening effect still remains. Rapid drying of the outside logs and timbers often causes similar cracks to appear on the longitudinal surfaces. Not all of these radial cracks close when seasoning is complete; some gradually open and remain a permanent source of weakness for a reason which we shall now explain.

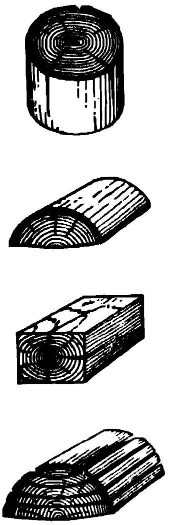

Fig. 9.—Effects of Shrinkage.

Looking at Fig. 14, we note that the cells in medullary rays are elongated in a direction perpendicular to the longitudinal elements. Since cells in the rays obey laws of shrinkage similar to those governing the behavior of the longitudinal elements, it is at once apparent that the rays will shrink in the longitudinal and tangential direction but not radially, whereas the longitudinal elements will shrink radially and tangentially but not longitudinally. Consequently, the lateral shrinkage of the ray in the longitudinal direction will be hindered by the adjoining longitudinal elements and the length of the ray will be shortened by the radial shrinkage of the longitudinal elements. The mutually perpendicular tensile and compressive forces thus produced are often sufficient to break the bond between the ray and the adjacent longitudinal fibers. Once the bond is broken, further circumferential shrinkage operates to widen rather than to close the breach.

In woods like oak, where the number of pith rays is very large, it is probable that the slight longitudinal shrinkage is due principally to lateral shrinkage of the rays. Also, the resistance offered by the rays to oppose radial shrinkage of the wood and the great shrinkage of the summer wood are the reasons why the tangential shrinkage of wood is always more than the radial shrinkage. The difference in shrinkage in these two directions is the cause of much difficulty in drying. Besides producing the checks in logs and sawn timbers, this difference between the tangential and radial shrinkage also causes the flat surfaces of a sawn log to become convex, as shown in Fig. 9.

When hardwoods, like oak, are quickly dried the water is evaporated more rapidly from the outside than it can be brought to the surface. As a result the outer portion of the piece checks; or, if it has sufficient plasticity under the influence of heat and moisture, the surface may take a set and harden just as wood bent in steam retains its shape after drying. If drying continues, the interior of the stick shrinks and the circumferential tension in the outer shell is relieved. Further shrinkage of the piece, as a whole, is diminished by the rigidity of the outer shell. This brings about a gradual reversal of stress in the shell and causes radial tension in the interior. If the radial tension becomes excessive, rupture will occur, as shown in Fig. 10. This phenomenon is called *case-hardening* or *honey-combing*. It may exist in lumber without the cracks being noticed, but is revealed immediately upon sawing. A simple test for case-hardening is that used by Tiemann (see Fig. 11).

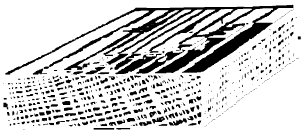

Fig. 10.—"Honeycombed" Board. The checks or cracks form along the pith-rays.

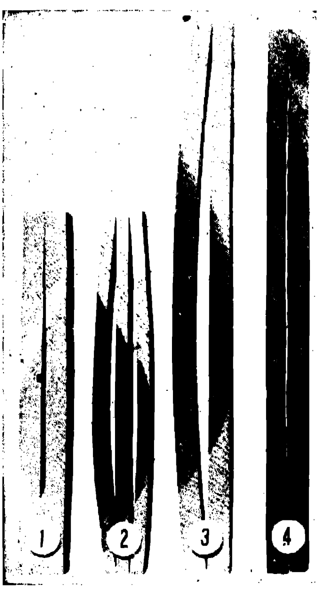

Fig. 11.—Illustrating the Elimination of Case-hardening in Kiln Dry Red Gum by Steaming at the End of the Drying Period. No. 1 sawn after no final steaming; Nos. 2 and 3 after eighteen minutes final steaming; No. 4 after thirty-six minutes final steaming. (J. E. Imrie, before Gum Lumber Mfrs. Assoc., Jan. 16, 1916.)

Rapid drying of green cedar and redwood at high temperatures often produces a collapse of the cell walls. This is brought about by the radial tensile stresses produced on the cell walls by the withdrawal of free water. Such defects lower the strength of the timber; they may be avoided by using lower initial temperatures in drying.

Dried pieces of wood greedily absorb water with an increase in volume until the cell walls are saturated, the *fiber-saturation* point is reached;* subsequent filling of the lumen in the cells is accompanied by no further swelling, Fig. 12.

The following average values for per cent moisture at fiber-saturation point were obtained by Tiemann (*Cir. No. 108*, Forest Service). Each result represents 40 or more tests per species of wood. In some cases individual values varied as much as 10 per cent from the averages.

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* Tiemann reported in *Proc. Soc. Am. For.*, Vol. 8, p. 313, that blue gum is an exception to the above rule, since it "begins to shrink immediately from green con- [illegible] out 70 to 90 per cent moisture."

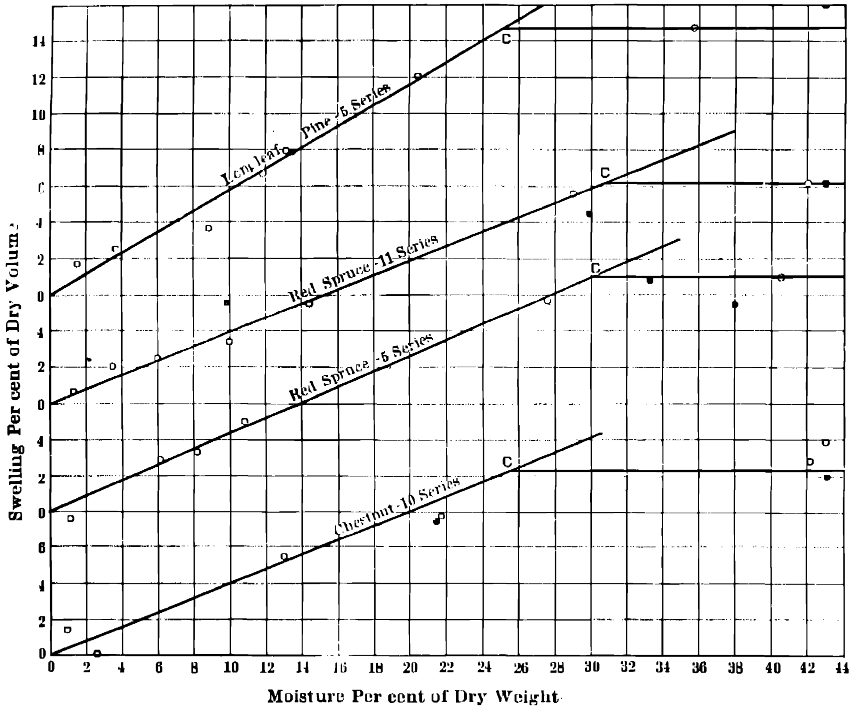

FIG. 12.—Relation between Swelling and Moisture. Each point is the average of from five to eleven specimens. Black dots indicate specimens that were kiln-dried and then allowed to reabsorb moisture. The fiber-saturation point is at *C*. (*Cir.* 108 of Forest Service.)

Species.	Per Cent.	Species.	Per Cent.
Southern yellow pine	25	Red spruce	31
Western hemlock	31	Chestnut	25
Western larch	27	Tamarack	30
Norway pine	29	Red gum	25
Douglas fir	23	White ash	20

Repeated wetting and drying weakens timber, causes expansion and contraction, and, in addition, produces conditions which promote decay. Timber must, therefore, be protected from moisture, if constancy in volume and its life are to be conserved. The swelling of wooden pipes and tanks after water is admitted often produces large stresses in [illegible] and timber. The amount of swelling and the stresses caused by it should be given careful consideration in design.

162. Amount of Shrinkage.—As a rule, if the sapwood is of the same density as the heartwood, the former will shrink more than the latter; but heavy heartwood shrinks more than light sapwood. Coniferous woods like pine, spruce, cedar, cypress and redwood shrink uniformly and do not check much in drying. Oak, beech, chestnut, elm, hickory, gum, and other hardwoods shrink considerably and check more or less, depending on the care exercised in drying.

In general, the radial shrinkage of wood is about 60 per cent of the tangential, and the longitudinal shrinkage is negligible. Therefore, the volumetric shrinkage is practically 1.6 times the tangential shrinkage. Experiments by the Forest Products Laboratory show that the shrinkage for all species of wood varies roughly as the first power of the specific gravity (ρ). From Bulletin No. 676 were obtained the following percentage relationships: volume shrinkage $= 28\rho$; radial shrinkage $= 9.5\rho$; tangential shrinkage $= 17\rho$.

Approximate values of the tangential shrinkage of air-dried material are given below, more accurate results appear in Table 1, Ch. VI.

APPROXIMATE SHRINKAGE OF A BOARD, OR SET OF BOARDS, 100 INCHES WIDE, DRYING IN THE OPEN AIR

Common Name of Species.	Lateral Shrinkage, Inches.
(1) Hardy catalpa; redwood; white or red cedar	2 –2½
(2) Cedar (Alaska, Incense, Port Orford); chestnut, cypress; Alpine, balsam, white, red fir; locust; eastern hemlock; light pines	3 –3½
(3) Ash; Douglas fir; tupelo or black gum; western hemlock, larch, heavy pines, poplar, spruce, sycamore, black walnut	3½–4
(4) Cottonwood, birch, maple	4 –4½
(5) Basswood, beech, elm, hickory, oak	4½–5½

PRINCIPAL NATIVE WOODS *

163. The sources, characteristics, and uses of the more important woods will now be briefly described. In the list which follows, an attempt has been made to arrange the various classes of wood in order of economic importance. Within a given class, however, there may be individual species which are of less value than species in a class farther down in the list. For example: Sugar pine, lodgepole pine, and tupelo gum are less valuable than hickory; but the pines and gums as groups are more valuable than hickory. The mechanical properties of many of these woods can be found in Ch. VI.

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* Compiled largely from Hough's *Handbook of Trees*, Snow's *Principal Species of Wood*, and *Bulletin* No. 232 of the U. S. Dept. of Agric.; see also *Wood Handbook*.

164. Southern Yellow Pine is the term applied to the species of yellow pine which are found in Southern States from Virginia to Texas; most of our supply now comes from Louisiana, Mississippi, Texas and North Carolina. Included in this group are longleaf, shortleaf, loblolly, Cuban and pond pine. Difficulty experienced in separating these species has brought about the use of this inclusive term and caused the adoption of grading rules for quality classification. From the standpoint of the lumber producer, longleaf and Cuban pine are the most desirable species. From the viewpoint of the consumer, if the standard grading rules are used in the selection of structural timbers of southern yellow pine the difference in strength and durability of members cut from trees of different species is unimportant. The heartwood of all species is durable in contact with the ground. The southern yellow pines are the most important source of dimension timber for all heavy construction. They also provide much lumber for joists, posts, piling, and building construction. When treated with preservatives the harder woods of this group make good ties and paving blocks.

165. White Pine is still found to a limited extent in the States north of the Ohio River and east of the Dakotas, most abundantly in Minnesota, Wisconsin and Maine. A somewhat inferior grade of white pine is obtained along the Rocky Mountains. It is a soft, uniform white wood which shrinks very little in seasoning, works easily, nails without splitting, and takes paint well. It is not very strong but quite durable. For window sash, interior trim and pattern making, the demand for this wood is very great.

166. Norway Pine is now found principally in the States bordering on the Great Lakes. It is a light wood of fair hardness and strength, but is not durable in contact with the ground. Some dimension timber, masts, spars, piling and interior trim are made of it. It is often sold for white pine.

167. Western Yellow Pine grows on the eastern slopes of the Rockies and in country westward to the coast. It is lighter, softer, weaker and less durable than longleaf pine, but heavier and stronger than white pine. It is considerably used for dimension timbers, ties and mine timbers; although unless treated, it is better fitted for trim and pattern making.

168. Sugar Pine, found in California and Oregon, is a very light soft wood resembling white pine; it has similar uses.

169. Lodgepole Pine, a timber found from the Rockies to the Pacific Coast, is a light, brittle, straight-grained wood of low strength. It is also difficult to season. This pine is used principally for poles, posts and ties.

170. White Oak of commerce includes true white, post, bur, overcup, swamp white, cow and chestnut oaks. Oak of this class may be found in the States east of Colorado, but the principal supply comes from the Virginias, Tennessee, Arkansas, Kentucky, Ohio and Missouri. These oaks are all hard, heavy, strong, tough, dense woods which are durable in contact with the soil. They shrink considerably and are likely to check in seasoning. The wood is capable of receiving a high polish. White oak is much used for furniture, cross-ties, agricultural implements, fence posts, wagon-stock, cooperage and baskets. These oaks are the most valuable of the hardwoods.

171. Red Oak of commerce includes red, pin, Spanish and black oaks. The sources of supply are the same as for white oak. The wood of the red oaks, though hard and strong, is more porous, somewhat lighter and weaker, and far less durable in contact with the soil than white oak. It is used chiefly for interior finish and furniture. It is easily impregnated with preservative and when so treated makes excellent cross-ties.

172. Live Oak is found along the coast of the southern Atlantic and Gulf States in California and Oregon. The wood is very heavy, hard, tough, strong, durable and difficult to work. It is used for implements, wagons and in ship building.

173. Douglas Fir is grown along the Pacific Coast, the most valuable forests being in Oregon, Washington and British Columbia. The wood is strong and rather brittle. The heartwood is durable in contact with the ground. It is the best structural timber of the northwest. This clear, straight-grained wood is widely used for building construction, dimension timber, ties, piles, boats, paving blocks, tanks, conduits and furniture.

174. Hemlock is found in the Great Lakes States, in southeastern Canada and from Maine to Georgia along the Appalachian range. Western hemlock grows on the Pacific Coast from Northern California to Alaska. The wood is light, soft and brittle. Western hemlock is moderately strong and fairly durable, but eastern hemlock is weak and not durable in contact with the ground. Hemlock holds nails well and is much used in house framing. Western hemlock, known to trade as West Coast hemlock, is considerably used for dimension timber and cross-ties.

175. Spruce.—Red spruce is found principally in New York, New England and West Virginia; white spruce in nearly all parts of Central Canada and in the Great Lakes States; Sitka spruce in Washington, Oregon and Idaho. The woods of these species are light and soft. They have low strength and fair durability. Spruce is used chiefly for paper pulp, railway ties, resonance wood, piles, aeroplanes and lumber.

176. Cypress grows along the eastern and Gulf coasts from Maryland to Texas and along the Mississippi Valley as far north as Illinois. Louisiana, Florida and Georgia are the chief producers. It is a wood of medium weight and strength which is rather difficult to season but very durable. Cypress is used for siding, shingles, sash, doors, tanks, silos and railway ties.

177. **Hard (Sugar) Maple** grows in all of the States east of Colorado but most abundantly in the Great Lakes region. The wood is heavy, tough, hard and strong, but not durable. The grain is often curly or has " bird's eyes." It is used for interior finish, flooring, furniture, ship and car construction. When treated this wood may be used for cross-ties.

178. **Soft (Red) Maple** is found in the region with hard maple. The wood is medium in weight, hard and strong, but inferior to hard maple. It is fairly easy to work and is used for furniture, cabinet making, turnery and gun stocks.

179. **Chestnut** grows on both slopes of the Appalachian Range, but is produced principally in the Virginias, Pennsylvania, Tennessee, and Connecticut. It is a light, soft, weak and brittle wood which is very durable in contact with the ground. The wood shrinks considerably and checks in seasoning, but works easily. Chestnut is much used for fence posts, poles and cross-ties; also for exposed constructions, furniture, and cooperage. Supply is scanty owing to ravages of a blight.

180. **Red (Sweet) Gum** grows in the same regions as cypress and is supplied most abundantly from Arkansas and Mississippi. The wood is not durable in the ground, soft, rather brittle and of moderate weight and strength. It is easily worked, but warps and twists in seasoning. When highly polished it makes attractive furniture and interior trim. Other uses are for flooring, slack cooperage, turnery and wagon stock.

181. **Tupelo (Sour) Gum** is found with red gum, but is most abundant in the Gulf States. It has about the same weight and strength as red gum but is tougher. This wood also is difficult to season and finds more or less use in the manufacture of boxes, furniture, wagon boxes, flooring and finishing.

182. **Hickory** is fast disappearing in this country; the present supply is obtained from Arkansas, Tennessee, and the Ohio basin. The more abundant varieties of hickory furnish very heavy, hard wood which is stronger and tougher than other native woods. Hickory checks and shrinks largely in seasoning and is difficult to work. It is subject to insect attack and not durable. The chief uses are for wagon stock, agricultural implements, axe-handles, hoops and baskets.

183. **Yellow Poplar (Whitewood)** is found in nearly all States east of the Mississippi River and south of the Great Lakes; it is gotten from the Virginias, Tennessee and Kentucky principally. The wood is light, soft, brittle, weak and easy to work. It shrinks considerably, but holds nails well and is fairly durable. Whitewood is a very valuable wood for

interior finish, furniture, shelving, drawers, wagon-bodies and boxes; it is also used for siding and paneling.

184. Basswood is scattered over the eastern half of the United States with the exception of the Southern Atlantic and Gulf Coasts; Wisconsin, Michigan, West Virginia and New York lead in production. The wood is soft, very light, weak, brittle and not durable. It shrinks considerably, but is very uniform and works easily. Although slightly inferior to whitewood, it is used for similar purposes.

185. Redwood grows abundantly along the coast of California. The wood is light, soft, straight-grained and very durable. In the West it is used for all kinds of lumber; ties, shingles, poles, paving blocks, tanks and conduits.

186. Yellow and Sweet Birch are found in the region east of the Mississippi River and north of the Gulf States, also in Southeastern Canada; Wisconsin, Michigan and Maine lead in production. The wood is heavy, hard, stiff, strong, and tough; but it is not durable when exposed. Although hard, it works easily and takes a high polish. Birch is much used for interior finish, furniture, turnery and carving.

187. Larch or Tamarack.—The eastern variety of this wood, generally called tamarack, is abundant in the Great Lakes region, New England, northern and eastern Canada. Western larch is found principally along the Columbia River Valley. The Western variety is of medium weight, rather tough, hard, and durable, but somewhat less strong than Douglas fir or western hemlock. It is used for lumber, lath, cross-ties, poles and slack cooperage. Tamarack is of approximately the same weight and strength as Western larch. Its uses are similar.

188. Ash.—Varieties of ash are found in nearly all States east of the Rockies. Black ash is confined to the Northern States of this region, but the white and green species are widely found. The wood of the white and green ashes is heavy, hard, strong and fairly tough. It is straight grained, shrinks little in seasoning and can be polished. It is used for finishing lumber, in wagon construction, farm implements, furniture and cabinet work. Black ash makes a lighter, inferior wood to that of the white or green ashes. It is used as a substitute for them and in basket making.

189. Red and White Cedar.—White cedar is found along the eastern coast and around the Great Lakes; red cedar grows in the region east of Colorado and north of Florida. Western red cedar is grown largely in Washington, Oregon, Idaho and Montana. Cedar wood is very light, soft, weak and brittle. Its low shrinkage and great durability, when exposed, make cedar valuable for shingles, siding, posts, poles and ties. Red cedar is much used for moth-proof chests.

190. Beech grows in the region east of the Mississippi and in southeastern Canada. The wood is heavy, hard, strong, tough, but not durable in contact with the soil. It shrinks and checks considerably in seasoning. It is used for furniture, plane-stocks, handles and shoe-lasts.

191. Elm.—White and slippery elms grow in the States east of Colorado; rock elm is found largely in Michigan and the States bordering on the Ohio River. The wood of the slippery and rock elms is heavy, hard, strong, tough, durable and difficult to split. The wood of white elm is somewhat inferior to that of the rock and slippery elms. Elm wood is used for agricultural implements, wheel-stock, boats, furniture, cross-ties, posts, and poles.

192. Cottonwood is found scattered over the region east of the Rockies, excepting in Maine; abundantly in Arkansas, Mississippi, Louisiana, and Tennessee. It is a soft, weak wood similar to whitewood but inferior in quality. It is considerably used for slack cooperage, fencing and paper pulp.

193. Black Walnut is found over the eastern half of the United States with the exception of Southern Atlantic and Gulf Coasts; Indiana, Ohio and Missouri are principal producers. Some varieties are obtainable from New Mexico, Arizona and California. The wood is of medium weight, hard, strong and easily worked. It has a dark chocolate color and is susceptible of a high polish. Owing to scarcity, its usage is confined largely to making of cabinets, furniture and gun stocks.

194. Sycamore is most abundantly grown in the Ohio and Mississippi basin, although common in most States east of Colorado. The wood is of medium weight, hardness and strength. It is rather brittle, difficult to work, and liable to check and warp in seasoning. Sycamore makes a pleasing appearance when quarter-sawn. It is used for interior trim, cabinet making, tobacco boxes, and cooperage.

195. Eucalyptus is a rapidly growing Australian tree of which a large number of varieties have been transplanted in California. Blue gum (*Eucalyptus Globulus*) is the most important of these. This durable wood is very heavy, hard, tough, and strong, comparing favorably in these respects with hickory. It is, however, extremely difficult to season, since it checks and warps very badly. From results obtained in Australia, it is predicted that the American blue gum will furnish a satisfactory wood for cross-ties, fence-posts, poles, piles, paving blocks and wagon-stock.

196. Catalpa is grown in Mississippi, Alabama, Georgia, and Florida; and hardy catalpa in Missouri, Illinois, Indiana, Kentucky and Tennessee. The wood of the two species is similar, being light, soft, and weak. It is very durable in contact with the ground and makes excellent fence posts and poles. If well protected with tie-plates it also serves for cross-ties.

The very rapid growth which is characteristic of the tree has led to the planting of it for such purposes.

THE IDENTIFICATION OF WOODS *

197. The Microscopic Structure of Wood.—Thus far we have considered the structure of wood which is readily discerned by the naked eye. With a microscope it has been ascertained that a few definite types of cells and fibers form the structures of all woods. Inasmuch as the recognition of these types of cells, as well as their arrangement and condition forms an important aid not only in identifying species, but also in accounting for mechanical properties, a brief account of them is made. There are four main types of these microscopic elements which, with numerous transitional forms, make up the structure of timber. These are (1) *tracheids*, (2) *parenchyma*, (3) *vessels*, (4) *wood fibers*. The two first-mentioned constitute the wood of the conifers, but all four types are found in varying amounts in broad-leaved trees.

Tracheids are slim polygonal cells provided with tapering ends. They are small and of little importance in the hardwoods; but in the conifers where they form the main constituents of the wood they range from 0.05 to 0.35 in. in length with a diameter of one-fiftieth to one one-hundredth of the length. The side walls of the tracheids are perforated with *bordered pits* which are funnel-like depressions most thickly found near the ends of the cell (see Fig. 13). Through the thin walls at the bottoms of these pits the sap flows from one cell to another. In Douglas fir, spiral ridges are found on the inside of the tracheids, while in long leaf and Norway pine the ray tracheids have irregular dentations on the inner surfaces.

Parenchyma are subordinate elements, which, like the tracheids, may be arranged end to end in a vertical line, thus forming the wood parenchyma fibers; or grouped in bundles with their long axes extending radially, they compose the entire pith rays of the hardwoods and the main part of the rays in softwoods. Sometimes, as in white oak, chestnut and hickory, the wood parenchyma fibers are arranged parallel to the vessels in the rings and appear as fine concentric lines on the cross-section. In some woods they form the boundaries of the rings; in some they are scattered through the wood irregularly; in others they are arranged in radial planes, and in still others they surround the larger vessels. Parenchyma are minute, thin-walled elements tapering at the ends and subdivided by transverse walls into short, prismatic cells. The side-walls of parenchyma are dotted with minute cylindrical depressions called *simple pits* as in Fig. 13*F*.

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* For a more complete discussion of the microscopic structure and the identification of woods, the reader is referred to Record's *Economic Woods* and Hough's *American Woods*.

By pressure of large bordering vessels the parenchyma running vertically are sometimes flattened into the conjugate form shown in Fig. 13*H*. In oak, hickory and walnut the individual cells of the vertical parenchyma are often separated by crystals of calcium oxalate, see Fig. 13*G*.

Vessels are small pipe-like elements of indefinite length, the walls of which are covered with bordered pits (Fig. 13*K*). The diameter of vessels is quite variable, sometimes reaching 0.02 in oak, but more often it is less than 0.01 in. While growing, constrictions are produced in the side-walls, thus indicating the segments of growth. These segments may fit together (1) in a perfect transverse plane, (2) in an oblique plane, or (3) as in oak and gum, the faces of the segments may be oblique and have blind ends extending beyond the main line of constriction. In type (1) the opening from one segment to another is round, but in (2) and (3) the perforations may be scalariform as in Fig. 13*L*. Vessels in the sapwood serve as vertical water supply lines for the growing portion of the tree, but in the heartwood they are frequently clogged with sac-like protrusions from adjacent parenchyma cells. These protrusions are called *tyloses*.

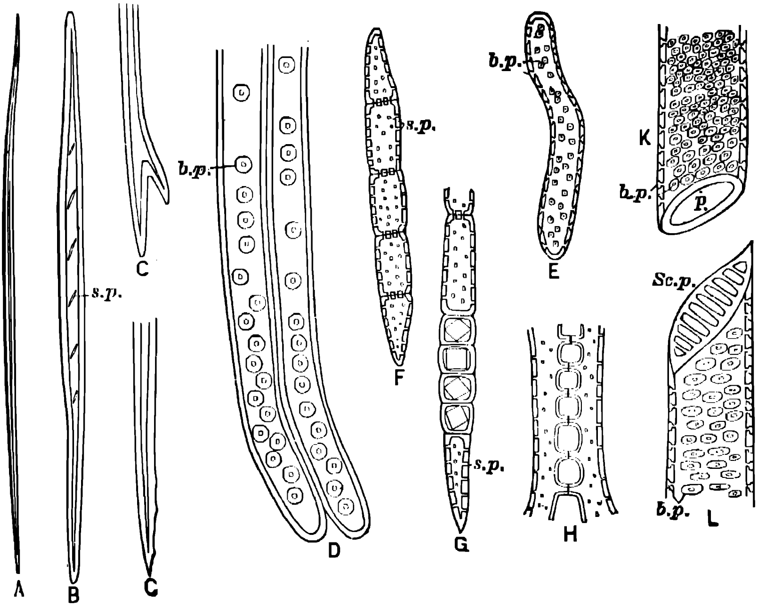

FIG. 13.—Types of Wood Cells.

A, wood fiber with narrow lumen; *B*, wood fiber with wider lumen and simple pits (*s. p.*); *C*, wood fiber with saw-toothed end; *C′*, wood fiber with forked end; *D*, tracheids with bordered pits (*b. p.*) from pine; *E*, tracheid from oak; *F*, wood parenchyma fiber with individual cells and simple pits (*s. p.*); *G*, wood parenchyma with crystals of calcium oxalate from walnut; *H*, conjugate parenchyma cells; *K*, part of segment of a vessel with simple perforation (*p.*); *L*, part of segment of a vessel with scalariform perforation (*Sc. p.*). All much enlarged. (After Record.)

Wood fibers are thin elongated cells tapering to a point at either end. They have thick walls which are ordinarily indented by inclined slit-like simple pits, see Fig. 13*B*. In mahogany the fibers are divided by cross partitions (septate fibers); in other woods the fibers are often forked at the ends (Fig. 13*C*′), a condition which decreases the cleavability of the wood. Wood fibers vary from a fiftieth to a tenth of an inch in length. They are found most commonly in the central portion of the annual rings of the hardwoods and are an important source of strength, toughness and hardness.

As mentioned before these various types of fibers grade into each other by transitional stages. Thus the wood fibers exhibit forms approaching the tracheids in some woods and approximating wood parenchyma in others, and the tracheids sometimes grade into the vessels.

198. The Structure of Coniferous Woods.—In Fig. 14 are shown (1) a sector of spruce in natural size and (2) a part of one ring from the same magnified 100 times but oriented to correspond with piece (1). Looking at the upper face of piece (2) we are at once impressed by the regular arrangement of the tracheids in radial rows. From left to right they become flattened radially showing the increase in density in passing from the spring wood to the summer wood. On the lower front portion of this piece we notice also the bordered pits, of which enlarged types are shown at *a*, *b* and *c*.

The dark lines in piece (1) represent the medullary rays of which five are exposed on the right face of piece (2). One of these rays is seen in section on the front face of piece (2). It will be noted that the cells in the rays are elongated radially and that each ray is one cell wide (uniseriate) and several cells deep. In this wood, the top and bottom cells of each ray are tracheids (*n*), but the intermediate cells are parenchyma (*m*).

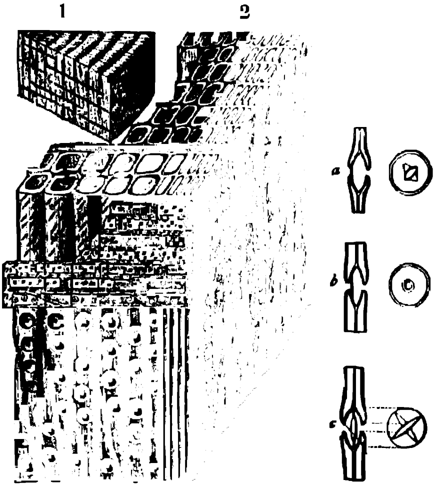

Fig. 14.—Wood of Spruce. 1, natural size; 2, small part of one ring magnified 100 times. The vertical tubes are wood-fibers, in this case all "tracheids." *m*, medullary or pith ray; *n*, transverse tracheids or pith-ray; *a*, *b*, and *c*, bordered pits of the tracheids, more enlarged.

The above example is typical of the regularity of arrangement of the cell structure in coniferous wood. In pine, spruce, Douglas fir, and tamarack vertical and radial resin ducts are found, which are interconnected here and there to permit the passage of resin. These ducts are often large enough to be distinguished by the naked eye. They are long canals bounded by groups of thin-walled cells, termed epithelial cells. Fig. 15 shows a cross-section of shortleaf pine which passes through a vertical resin duct. Radial resin ducts are commonly inclosed in multiseriate rays. Such ducts may often be formed by injury; chipping the outer sapwood of longleaf pine opens the resin ducts and affords a method of securing turpentine and allied products.

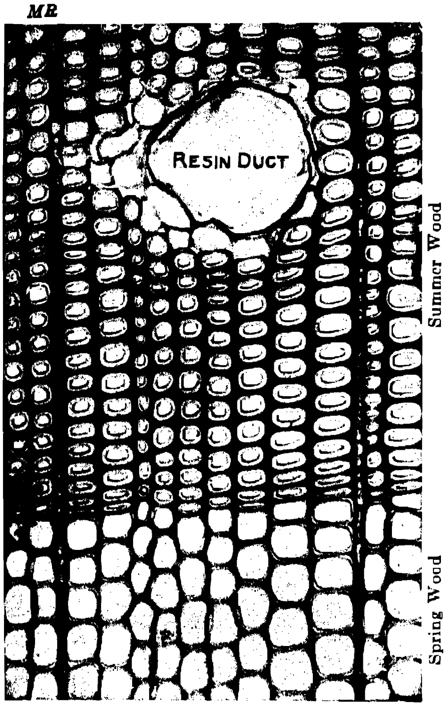

Fig. 15.—Cross-section of Shortleaf Pine, Showing Resin Duct Surrounded by Epithelial Cells. (*Bul.* 101, U. S. Dept. Agric., Pl. 1. Magnification = 125 diam.)

Tyloses are sometimes found in tracheids adjoining parenchymatous cells, but in conifers they are more often noticed in the resin ducts. Norway pine, Western pine, white pine, and sugar pine, are the main coniferous woods which have abundant tyloses (see Art. 208).

199. The Structure of Wood from Broad-leaved Trees.—As we have previously mentioned, the arrangement of the cell elements in the wood of the broad-leaved trees is far more varied and complex than in the conifers. We shall consider two examples, red oak to illustrate ring-porous woods and sugar maple to illustrate diffuse-porous woods.

The magnified cross-sectional view of red oak in Fig. 16 shows very clearly the irregular grouping of the large vessels in the spring wood, with a more or less gradual transition to smaller ones scattered here and there through the summer wood. In good oak these vessels occupy less than 10 per cent of the volume of the wood, but in poorer varieties they may amount to 25 per cent. In the middle of the annual ring the dark, solid looking patches represent the cut ends of the wood fibers. The thicker the walls of these fibers and the greater the proportion of them in the wood, the stronger and tougher will it be. In good timber the fibers constitute one-half of the volume. Two medullary rays are also exposed

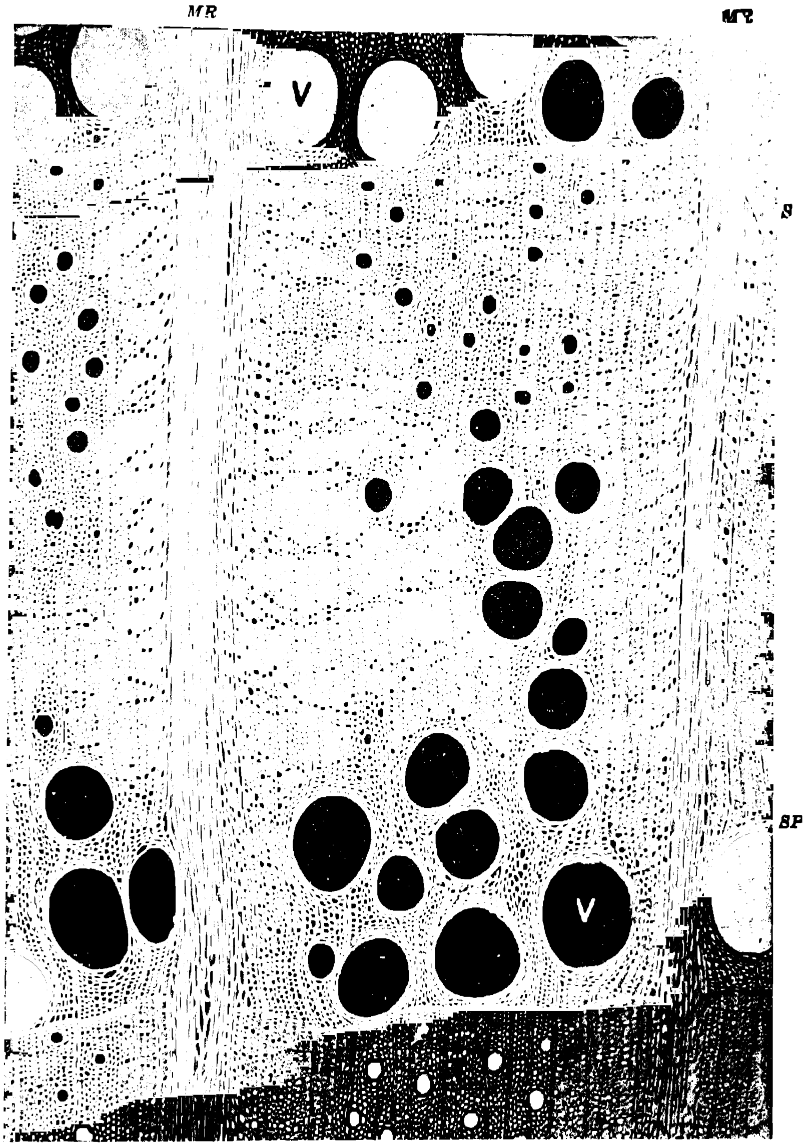

Fig. 16.—Photomicrograph of Cross-section of Red Oak, a Ring-porous Wood.

SP, spring wood (note open pores); *S*, summer wood; *F*, fibers; *V*, vessels or pores; *MR*, medullary ray. (Prepared by the Forest Products Laboratory Forest Service, U. S. Dept. of Agric. Magnified 40 diameters.)

in this view. The width of the band of cells composing these rays is a decided contrast to the uniseriate rays of the conifers. In the oaks, rays are often a hundred cells in width and an inch or more in height. It will be observed, however, that they always taper in width, at the top and bottom, to a single cell. Fig. 17 brings out the comparative size of the medullary rays and the ring-thickness in oak. All of the cells in the rays of the dicotyledons are parenchyma. Some of the individual parenchyma can be distinguished in Fig. 16. Beside the medullary rays of large size other uniseriate pith rays of parenchymatous cells may also be seen in Fig. 16. The total proportion of rays in good white oak generally lies between 15 and 25 per cent.

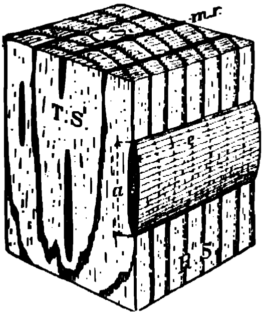

Fig. 17.—Block of Oak. *CS*, cross-section; *RS*, radial section; *TS*, tangential section; *mr*, medullary or pith ray; *a*, height, *b*, width, and *e*, length of a pith-ray.

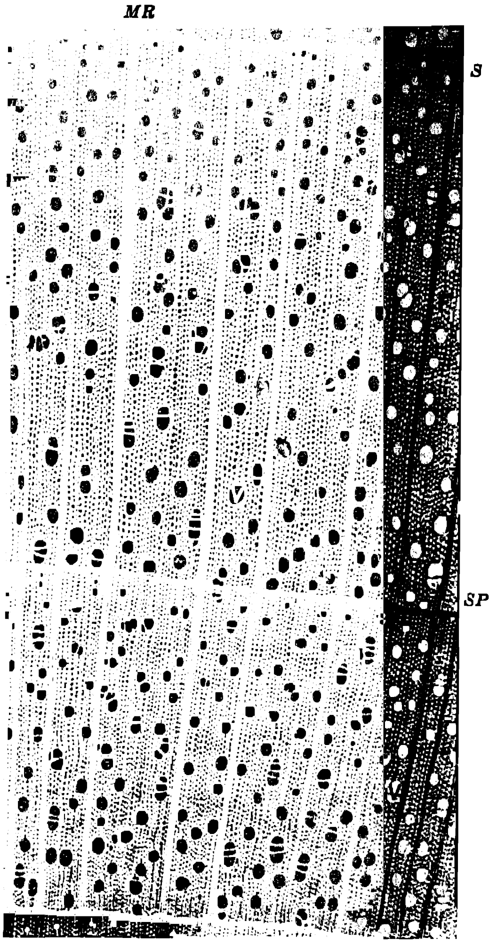

Fig. 18.—Cross-section of Hard Maple.

(Note tendency of pores, *V*, to form radial groups. Spring wood, *SP*, is much like the summer wood, *S*. Narrow medullary ray, *MR*. Fibers, *F*. Magnification = 34 diameters. (Photo prepared by Forest Products Laboratory, Forest Service, U. S. Dept. Agric.)

The arrangement of pores in a ring-porous wood like the sugar maple is more uniform, the diameters are smaller, and the variation in size is less than in the oak (Fig. 18). Scarcely any difference is to be noted in the size of the vessels in the spring wood and summer wood, but there is a tendency toward radial grouping of two to four cells which is plainly marked. The medullary rays are much narrower than in the oak but broader than in the conifers. When the wood is quarter-sawed these rays produce a silvery appearance. There are, however, numerous intermediate pith rays of one-cell width in evidence. A further distinguishing feature of this wood is the distinct markings which limit the growth rings.

Tyloses are abundantly found in the vessels of the following hardwoods: in white, Garry, over-cup, bur, swamp, cow, valley and post oaks, in most hickories, in chestnut, black locust, and osage orange. Tyloses apparently increase the resistance of the wood to the decay and also decreases the penetrance to preservatives.*

200. The Use of a Key in Distinguishing Woods.†—Nobody need expect to be able to use successfully any key for the distinction of woods or of any other class of natural objects without some practice. This is especially true with regard to woods, which are apt to vary much, and when the key is based on such meager general data as the present. The best course to adopt is to supply one's self with a small sample collection of woods accurately named.‡ Small, polished tablets are of little use for this purpose. The pieces should be large enough, if possible, to include pith and bark, and of sufficient width to permit ready inspection of the cross-section. By examining these with the aid of the key, beginning with the better-known woods, one will soon learn to see the features described and to form an idea of the relative standards which the maker of the key had in mind. To aid in this, the accompanying illustrations will be of advantage. When the reader becomes familiar with the key, the work of identifying any given piece will be comparatively easy. The material to be examined must, of course, be suitably prepared. It should be moistened; all cuts should be made with a very sharp knife or razor and be clean and smooth, for a bruised surface reveals but little structure. The most useful cut may be made along one of the edges. Instructive, thin, small sections may be made with a sharp penknife or razor, and when placed on a piece of thin glass, moistened and covered with another piece of glass, they may be examined by holding them toward the light.

Finding, on examination with the magnifier, that it contains pores, we know it is not coniferous or non-porous. Finding no pores collected in the

* From researches of Miss E. Gerry. See *Jour. Agric. Research*, Vol. 1, p. 464.

† The remainder of this chapter is mainly the joint product of Dr. B. E. Fernow and Mr. Filibert Roth. Also see *The Properties and Uses of Wood*, by A. Koehler.

‡ Hough's *Wood Sections* will be found both helpful and pleasing. About three hundred and fifty species of American woods are now so prepared by Romeyn B. Hough Co., Lowville, N. Y.

spring wood portion of the annual ring, but all scattered (diffused) through the ring, we turn at once to the class of " diffuse-porous woods." We now note the size and manner in which the pores are distributed through the ring. Finding them very small and neither conspicuously grouped, nor larger nor more abundant in the spring wood, we turn to the third group of this class. We now note the pith-rays, and finding them neither broad nor conspicuous, but difficult to distinguish even with the magnifier, we at once exclude the wood from the first two sections of this group and place it in the third, which is represented by only one kind, cottonwood. Finding the wood very soft, white, and on the longitudinal section with a silky luster, we are further assured that our determination is correct. We may now turn to the list of woods and obtain further information regarding the occurrence, qualities, and uses of the wood.

Sometimes our progress is not so easy; we may waver in what group or section to place the wood before us. In such cases we may try each of the doubtful roads until we reach a point where we find ourselves entirely wrong and then return and take up another line; or we may anticipate some of the later-mentioned features and, finding them apply to our specimen, gain additional assurance of the direction we ought to travel. Color will often help us to arrive at a speedy decision. In many cases, especially with conifers, which are rather difficult to distinguish, a knowledge of the locality from which the specimen comes is at once decisive. Thus, Northern white cedar, and bald cypress, and the cedar of the Pacific will be identified even without the somewhat indefinite criteria given in the key.

Key to the More Important Woods of North America

I. NON-POROUS WOODS

Includes all coniferous woods.

A. Resin-ducts wanting.*

  1. No distinct heartwood.

    a. Color effect yellowish white; summer wood darker yellowish (under microscope pith-ray without tracheids)........................FIRS

    b. Color effect reddish (roseate) (under microscope pith-ray with tracheids) HEMLOCK

  2. Heartwood present, color decidedly different in kind from sapwood.

    a. Heartwood light orange-red; sapwood pale lemon; wood heavy and hard..YEW

    b. Heartwood purplish to brownish red; sapwood yellowish white; wood soft to medium hard, light, usually with aromatic odor....RED CEDAR

    c. Heartwood maroon to terra cotta or deep brownish red; sapwood light orange to dark amber, very soft and light, no odor; pith-rays very distinct, specially pronounced on radial section............. REDWOOD

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* To discover the resin-ducts a very smooth surface is necessary, since resin-ducts are frequently seen only with difficulty, appearing on the cross-section as fine whiter or darker spots normally scattered singly, rarely in groups, usually in the summer wood of the annual ring. They are often much more easily seen on radial, and still more so on tangential sections, appearing there as fine lines or dots of open structure of different color, or as indentations or pin-scratches in a longitudinal direction.

3. Heartwood present, color only different in shade from sapwood, dingy-yellowish brown.
   - *a*. Odorless and tasteless.................................. BALD CYPRESS
   - *b*. Wood with mild resinous odor, but tasteless............. WHITE CEDAR
   - *c*. Wood with strong resinous odor and peppery taste when freshly cut. INCENSE CEDAR

B. Resin-ducts present.

1. No distinct heartwood; color white, resin-ducts very small, not numerous. SPRUCE
2. Distinct heartwood present.
   - *a*. Resin-ducts numerous, evenly scattered through the ring.
     - *a'*. Transition from spring wood to summer wood gradual; annual ring distinguished by a fine line of dense summer-wood cells; color white to yellowish red; wood soft and light. SOFT PINES *
     - *b'*. Transition from spring wood to summer wood more or less abrupt; broad bands of dark-colored summer wood; color from light to deep orange; wood medium hard and heavy.... HARD PINES *
   - *b*. Resin-ducts not numerous nor evenly distributed.
     - *a'*. Color of heartwood orange-reddish; sapwood yellowish (same as hard pine); resin-ducts frequently combined in groups of 8 to 30, forming lines on the cross-section (tracheids with spirals). DOUGLAS FIR
     - *b'*. Color of heartwood light russet-brown; of sapwood yellowish brown; resin-ducts very few, irregularly scattered (tracheids without spirals).................................. TAMARACK

ADDITIONAL NOTES FOR DISTINCTIONS IN THE NON-POROUS GROUP.

Spruce is hardly distinguishable from fir, except by the existence of the resin-ducts, and microscopically by the presence of tracheids in the medullary rays. Spruce may also be confounded with soft pine, except for the heartwood color of the latter and the larger, more frequent, and more readily visible resin-ducts.

In the lumber-yard hemlock is usually recognized by color and the slivery character of its surface. Western hemlocks partake of this last character to a less degree.

Microscopically the white pine can be distinguished by having usually only one large pit, while spruce shows three to five very small pits in the parenchyma-cells of the pith-ray communicating with the tracheid.

The distinction of the pines is possible only by microscopic examination. The following distinctive features may assist in recognizing, when in the log or lumber-pile, those usually found in the market:

The light, straw color, combined with great lightness and softness, distinguishes the white pines (white pine and sugar-pine) from the hard pines (all others in the market), which may also be recognized by the gradual change of spring wood into summer wood. This change in hard pines is abrupt, making the summer wood appear as a sharply defined and more or less broad band.

The Norway pine, which may be confounded with the shortleaf pine, can be distinguished by being much lighter and softer. It may also, but more rarely, be con-

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* Soft and hard pines are arbitrary distinctions, and the two are not distinguishable at the common limit.

II. RING-POROUS WOODS

[Some of Group D and cedar-elm imperfectly ring-porous.]

- A. **Pores in summer wood minute, scattered singly or in groups, or in short broken lines, the course of which is never radial.**
  - 1. **Pith-rays minute, scarcely distinct.**
    - *a*. **Wood heavy and hard; pores in the summer wood not in clusters.**
      - *a′*. Color of radial section not yellow .... Ash
      - *b′*. Color of radial section light yellow; by which, together with its hardness and weight, this species is easily recognized. Osage Orange
    - *b*. **Wood light and soft; pores in the summer wood in clusters of 10 to 30.** Catalpa

founded with heavier white pine, but for the sharper definition of the annual ring, weight, and hardness.

The longleaf pine is strikingly heavy, hard, and resinous, and usually very regular and narrow-ringed, showing little sapwood, and differing in this respect from the shortleaf and loblolly pine, which usually have wider rings and more sapwood, the latter excelling in that respect.

If the pith is present in the cross-section, the following method, which was proposed by Mr. Arthur Koehler of the Forest Products Laboratory, serves to distinguish longleaf pine:

Make the pith and surrounding rings clearly visible by smoothing with a knife and moistening the smoothed surface. By the aid of a finely graduated rule and low-power lens measure the diameter of the pith. If it is less than 0.10 in. the specimen is not longleaf. In case the diameter of the pith is over 0.10 in., measure the diameter of the second annual ring, being careful to avoid mistake in identifying the second ring. On a piece of cross-sectional paper mark the diameter of pith as ordinates (y) and the diameter of the second annual ring as abscissas (x). Using scales of 1.0 in. = 0.05 for diameter of pith and 1.0 in. = 0.25 in. for diameter of second ring, draw a smooth curve through the following points: $x = 0.40$, $y = 0.09$; $x = 0.75$, $y = 0.12$; $x = 1.05$, $y = 0.151$; $x = 1.50$, $y = 0.198$; $x = 2.00$, $y = 0.257$. From the curve find diameter of pith corresponding to the measured diameter of the second ring. If this value is smaller than the measured diameter of pith, the specimen is longleaf, or very rarely Cuban pine. If the measured diameter of pith is nearly the same as the chart diameter, make check measurements on the other end of the specimen.

The following convenient and useful classification of pines into four groups, proposed by Dr. H. Mayr, is based on the appearance of the pith-ray as seen in a radial section of the spring wood of any ring:

Section I. Walls of the tracheids of the pith-ray with dentate projections.

- *a*. One to two large, simple pits to each tracheid on the radial walls of the cells of the pith-ray.—Group 1. Represented in this country only by *P. resinosa*.
- *b*. Three to six simple pits to each tracheid, on the walls of the cells of the pith-ray.—Group 2. *P. tæda, palustris,* etc., including most of our "hard" and "yellow" pines.

Section II. Walls of tracheids of pith-ray smooth, without dentate projections.

- *a*. One or two large pits to each tracheid on the radial walls of each cell of the pith-ray.—Group 3. *P. strobus, lambertiana*, and other true white pines.
- *b*. Three to six small pits on the radial walls of each cell of the pith-ray.—Group 4. *P. parryana* and other nut-pines, including also *P. balfouriana*.

2. **Pith-rays** very fine, yet distinct; pores in summer woods usually single or in short lines; color of heartwood reddish brown; of sapwood yellowish white; peculiar odor on fresh section........................SASSAFRAS
3. **Pith-rays** fine, but distinct.
    - *a*. Very heavy and hard; heartwood yellowish brown.......BLACK LOCUST
    - *b*. Heavy; medium hard to hard.
        - *a′*. Pores in summer wood very minute, usually in small clusters of 3 to 8; heartwood light orange-brown..........RED MULBERRY
        - *b′*. Pores in summer wood small to minute, usually isolated; heartwood cherry-red...............................COFFEE-TREE
4. **Pith-rays** fine, but very conspicuous, even without magnifier. Color of heart wood red; of sapwood pale lemon...............HONEY-LOCUST

B. Pores of summer wood minute or small, in concentric wavy and sometimes branching lines, appearing as finely feathered hatchings on tangential section.

1. **Pith-rays** fine, but very distinct; color greenish white. Heartwood absent or imperfectly developed...............................HACKBERRY
2. **Pith-rays** indistinct; color of heartwood reddish brown; sapwood grayish to reddish white...ELMS

C. Pores of summer wood arranged in radial branching lines (when very crowded radial arrangement somewhat obscured).

1. Pith-rays very minute, hardly visible..........................CHESTNUT
2. Pith-rays very broad and conspicuous...............................OAK

D. Pores of summer wood mostly but little smaller than those of the spring wood, isolated and scattered; very heavy and hard woods. The pores of the spring wood sometimes form but an imperfect zone. (Some diffuse-porous woods of groups A and B may seem to belong here.)

ADDITIONAL NOTES FOR DISTINCTIONS IN THE RING-POROUS GROUP

Sassafras and mulberry may be confounded but for the greater weight and hardness and the absence of odor in the mulberry; the radial section of mulberry also shows the pith-rays conspicuously.

Honey-locust, coffee-tree and black-locust are also very similar in appearance. The honey-locust stands out by the conspicuousness of the pith-rays, especially on radial sections, on account of their height, while the black locust is distinguished by the extremely great weight and hardness, together with its darker brown color.

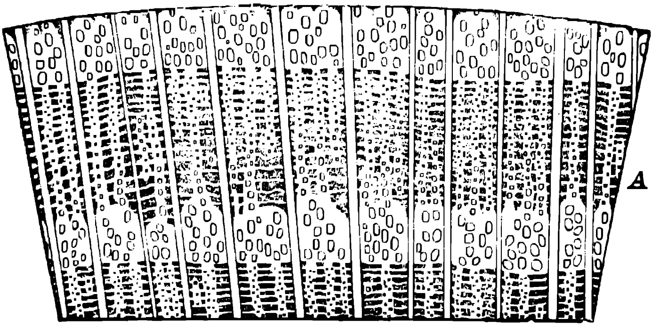

FIG. 19.—Wood of Coffee-tree.

1. Fine concentric lines * (not of pores) as distinct, or nearly so, as the very fine pith-rays; outer summer wood with a tinge of red; heartwood light reddish brown...HICKORY
2. Fine concentric lines,* much finer than the pith-rays; no reddish tinge in summer wood; sapwood white; heartwood blackish..........PERSIMMON

The ashes, elms, hickories, and oaks may, on casual observation, appear to resemble one another on account of the pronounced zone of porous spring wood. The sharply defined large pith-rays of the oak exclude these at once; the wavy lines of pores in the summer wood, appearing as conspicuous, finely feathered hatchings on tangential section, distinguish the elms; while the ashes differ from the hickory by the very conspicuously defined zone of spring-wood pores, which in hickory appear more or less interrupted. The reddish hue of the hickory and the more or less brown hue of the ash may also aid in ready recognition. The smooth, radial surface of split hickory will readily separate it from the rest.

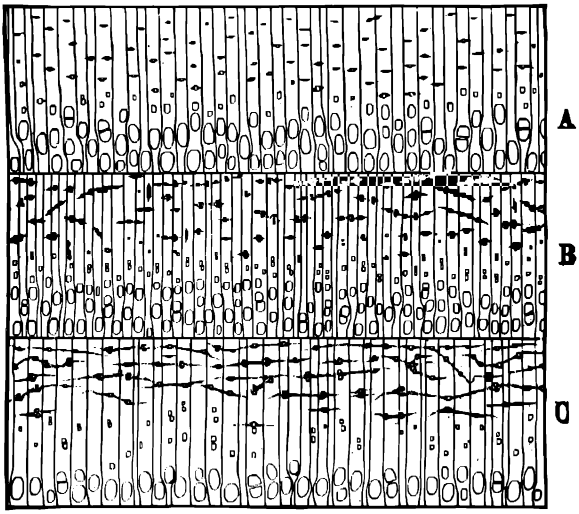

FIG. 20.—*A*, Black Ash; *B*, White Ash; *C*, Green Ash.

The different species of ash may be identified as follows:

1. Pores in the summer wood more or less united into lines by parenchyma fibers.
    - *a.* The lines short and broken, occurring mostly near the limit of the ring. WHITE ASH
    - *b.* The lines quite long and conspicuous in most parts of the summer wood. GREEN ASH
2. Pores in the summer wood not united into lines, or rarely so.
    - *a.* Heartwood reddish brown and very firm.....................RED ASH
    - *b.* Heartwood grayish brown and much more porous...........BLACK ASH

In the oaks two groups can be readily distinguished by the manner in which the pores are distributed in the summer wood. In the white oaks the pores are very fine and numerous and crowded in the outer part of the summer wood, while in the black

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* These fine concentric lines are the several ends of wood parenchyma fibers.—M. O. W.

ADDITIONAL NOTES—*continued*

or red oaks the pores are larger, few in number, and mostly isolated. The live oaks, as far as structure is concerned, belong to the black oaks, but are much less porous, and are exceedingly heavy and hard.

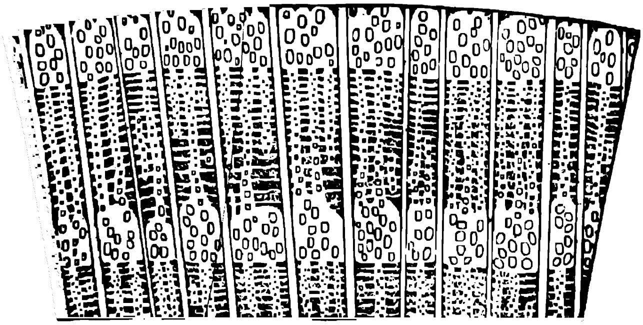

Fig. 21.—Wood of Red Oak. (For White Oak see Fig. 2.)

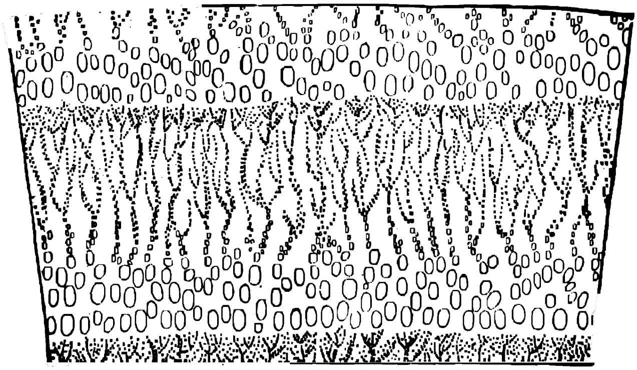

Fig. 22.—Wood of Chestnut.

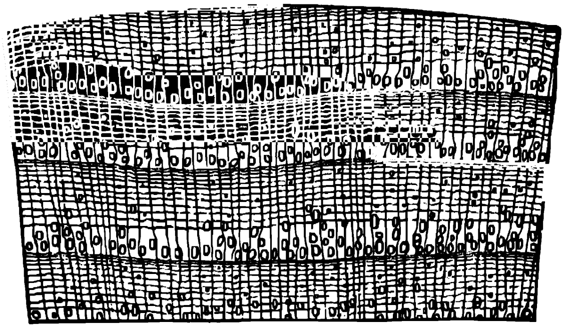

Fig. 23.—Wood of Hickory.

III. DIFFUSE-POROUS WOODS

[A few indistinctly ring-porous woods of Group II, D, and cedar-elm may seem to belong here.]

A. Pores varying in size from large to minute; largest in spring wood, thereby giving sometimes the appearance of a ring-porous arrangement.

1. Heavy and hard; color of heartwood (especially on longitudinal section) chocolate-brown . . . . BLACK WALNUT

2. Light and soft; color of heartwood light reddish brown . . . . BUTTERNUT

B. *Pores all minute and indistinct; most numerous in spring wood, giving rise to a lighter-colored zone or line (especially on longitudinal section), thereby appearing* sometimes ring-porous; wood hard, heartwood vinous-reddish; pith-rays very fine, but very distinct. (See also the sometimes indistinct ring-porous cedar-elm, and occasionally winged elm, which are readily distinguished by the concentric wavy lines of pores in the summer wood.) . . . . CHERRY

C. Pores minute or indistinct, neither conspicuously larger nor more numerous in the spring wood and evenly distributed.

1. Broad pith-rays present.

a. All or most pith-rays broad, numerous, and crowded, especially on tangential sections, medium heavy and hard, difficult to split.
SYCAMORE

b. Only part of the pith-rays broad.

a′. Broad pith-rays well defined, quite numerous; wood reddish white to reddish . . . . BEECH

b′. Broad pith-rays not sharply defined, made up of many small rays, not numerous. Stem furrowed, and therefore the periphery of section, and with it the annual rings, sinuous, bending in and out, and the large pith-rays generally limited to the furrows or concave portions. Wood white, not reddish.
BLUE BEECH

ADDITIONAL NOTES FOR DISTINCTIONS IN THE DIFFUSE-POROUS GROUP

Cherry and birch are sometimes confounded. The high pith-rays on the cherry or radial sections readily distinguish it; distinct pores on birch and spring-wood zone in cherry, as well as the darker vinous-brown color of the latter, will prove helpful.

Two groups of birches can be readily distinguishable, though specific distinction is not always possible.

1. Pith-rays fairly distinct, the pores rather few and not more abundant in the spring wood; wood heavy, usually darker.
CHERRY BIRCH and YELLOW BIRCH

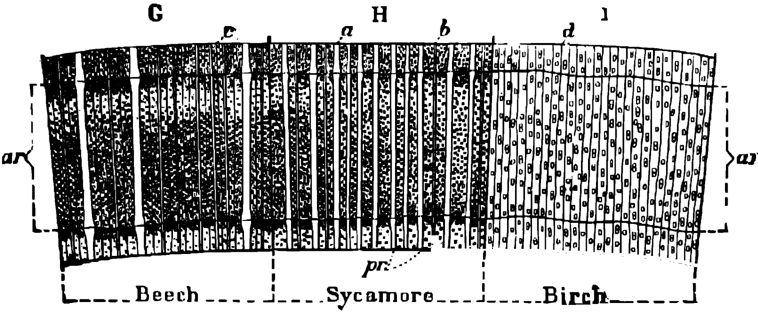

FIG. 24.—Wood of Beech, Sycamore, and Birch.

2. No broad pith-rays present.

- *a*. Pith-rays small to very small, but quite distinct.
  - *a′*. Wood hard.
    - *a″*. Color reddish white, with dark reddish tinge in outer summer wood.................................... Maple
    - *b″*. Color white, without reddish tinge.................. Holly
  - *b′*. Wood soft to very soft.
    - *a″*. Pores crowded, occupying nearly all the space between pith-rays.
      - *a‴*. Color yellowish white, often with a greenish tinge in heartwood.................... Tulip-poplar
Cucumber-tree
      - *b‴*. Color of sapwood grayish, of heartwood light to dark reddish brown......... Red (Sweet) Gum
    - *b″*. Pores not crowded, occupying not over one-third the pith-rays; heartwood brownish white to very light brown Basswood
- *b*. Pith-rays scarcely distinct, yet if viewed with ordinary magnifier, plainly visible.
  - *a′*. Pores indistinct to the naked eye.
    - *a″*. Color uniform pale yellow; pith-rays not conspicuous even on the radial section....................... Buckeye
    - *b″*. Sapwood yellowish gray, heartwood grayish brown; pith-rays conspicuous on the radial section.. .Tupelo (Sour) Gum
  - *b′*. Pores scarcely distinct, but mostly visible as grayish specks on the cross-section; sapwood whitish, heartwood reddish. Birch

3. Pith-rays not visible or else indistinct, even if viewed with magnifier.
   1. Wood very soft, white, or in shades of brown, usually with a silky luster. Cottonwood (Poplar)

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2. Pith-rays barely distinct, pores more numerous and commonly forming a more porous spring wood zone; wood of medium weight. Canoe or Paper-birch

The species of maple may be distinguished as follows:

1. Most of the pith-rays broader than the pores and very conspicuous. Sugar-maple

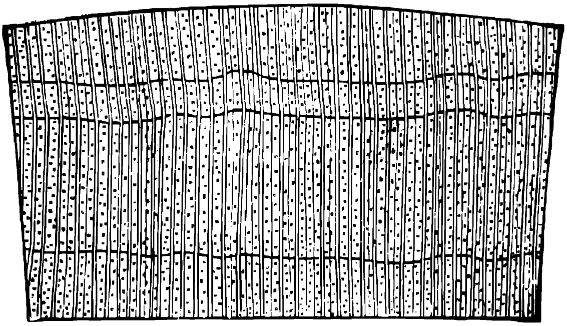

Fig. 25.—Wood of Maple.

ADDITIONAL NOTES—*continued*

2. Pith-rays not or rarely broader than the pores, fine but conspicuous.
    - *a.* Wood heavy and hard, usually of darker reddish color and commonly spotted on cross-section. . . . . .RED MAPLE
    - *b.* Wood of medium weight and hardness, usually light-colored. SILVER MAPLE

Red maple is not always safely distinguished from soft maple. In box-elder the pores are finer and more numerous than in soft maple.

The various species of elm may be distinguished as follows:

1. Pores of spring wood form a broad band of several rows; easy splitting, dark brown heart. . . . . .RED ELM
2. Pores of spring wood usually in a single row, or nearly so.
    - *a.* Pores of spring wood large, conspicuously so. . . . . .WHITE ELM
    - *b.* Pores of spring wood small to minute.
        - *a′.* Lines of pores in summer wood fine, not as wide as the intermediate spaces, giving rise to very compact grain. . . .ROCK-ELM
        - *b′.* Lines of pores broad, commonly as wide as the intermediate spaces. WINGED ELM
    - *c.* Pores in spring wood indistinct, and therefore hardly a ring-porous wood. . . . . .CEDAR-ELM

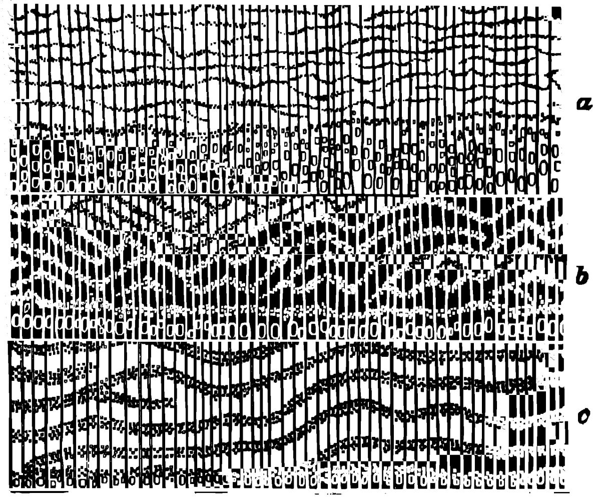

FIG. 26.—Wood of Elm. *a*, Red Elm; *b*, White Elm; *c*, Winged Elm.

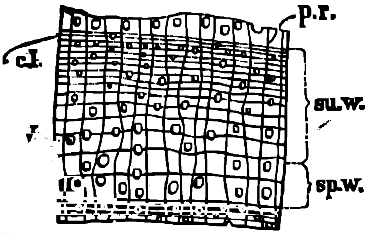

FIG. 27.—Walnut, *p. r.*, pith-rays; *c. l.*, concentric lines; *v*, vessels or pores; *su.w*, summer wood; *sp.w*, spring wood.

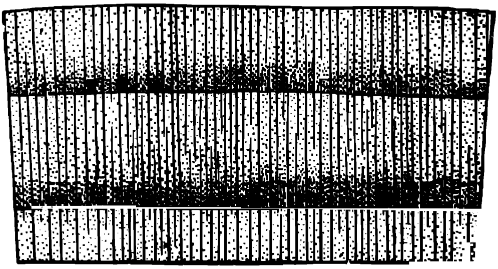

FIG. 28.—Wood of Cherry.

CHAPTER V

THE DETERIORATION AND PRESERVATION OF TIMBER[*]

DETERIORATION

201. The Durability of Wood.—The durability of wood is a decidedly variable property. If well-seasoned and kept in a dry place, if immersed in water, or if buried in the ground, it often lasts for centuries. Examples of sound wood piling which have been buried over a thousand years, wooden buildings which have stood for centuries, and many wooden relics can be cited as proof of this statement. When, however, unprotected wood is subjected to moisture, air and moderate warmth it decays. The rapidity with which it decays depends on external conditions, the species of the wood, its preliminary conditioning, and its structure. Thus in mines the life of timber sets of untreated red oak and pine is not over two or three years, in ties or fence posts it may reach four to six years, and unprotected pine bleachers may last ten years. In exposed structures decay nearly always starts at the sills and bottoms of posts and columns. Joints like Fig. 1 afford receptacles for the collection of water and snow with the result shown. On the other hand untreated fence posts of osage orange,

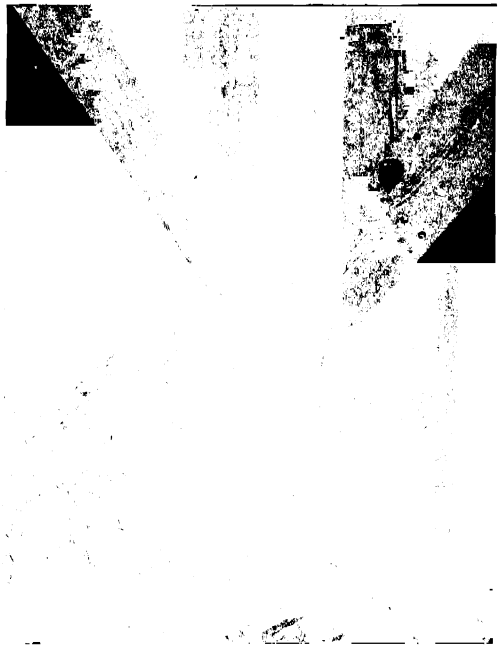

Fig. 1.—Decay at Joint and in Strut Supporting a Bleachers. (Teesdale in *Am. Lumberman*, Oct. 3, 1914.)

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[*] *Preservation of Structural Timber*, by H. F. Weiss, *Bulletins* Nos. 78, 118, 107, and 126 of the Forest Service, were the principal sources for the compilation of this chapter.

black locust and red cedar often last a quarter century or more;* the life of cedar poles may be estimated at fourteen years, but those of loblolly pine are likely to decay in one-third of that time. *In general, sapwood decays much more rapidly than heartwood.* Hence specifications call for a large proportion of heartwood in timbers to be exposed to the weather. A table showing the relative resistance of the heartwood of common native timbers follows.

DURABILITY OF HEARTWOOD OF TIMBERS UNDER CONDITIONS FAVORING DECAY

Highly Durable	*Medium Durability*	*Low Durability*	*Non-durable*
Cedar, red or white	Douglas fir	Beech	Aspen
Chestnut	Pine, southern yellow	Birch	Basswood
Cypress	Gum, red	Hemlock	Cottonwood
Locust, black	Larch, western	Maple	Fir, white
Oak, white	Pine, white	Oak, red	
Osage Orange	Tamarack	Pine, Norway	
Redwood		Spruce	

Besides decay, wood may be injured by the attack of insects, marine borers, and woodpeckers. It deteriorates under mechanical abrasion and may, of course, be entirely destroyed by fire.

202. Composition of Wood.—Wood is essentially an organic substance, made up of a skeleton of cellulose impregnated with lignin. Cellulose is a whitish substance, like starch ($C_6H_{10}O_5$) in composition, but more highly resistant to alcoholic fermentation. Lignin is also composed of carbohydrate compounds, but it is more soluble in acid than cellulose. Chemically, dry wood contains 49 per cent carbon, 44 per cent oxygen, 6 per cent hydrogen, and 1 per cent ash.

203. Causes of Decay.—The organic substances in wood are susceptible of attack both by bacteria and by fungi. The method by which bacteria decompose wood is probably similar in nature to a fungus attack. Fungi reproduce through thousands of minute particles, called "spores," which are blown about by the wind. The spores send out mycelia, which in turn destroy the wood tissue by the action of solvent chemicals, enzymes, which the mycelia secrete.

Only a small proportion of fungi destroy wood. Of this number some attack the lignin, others the cellulose, and still others consume both of these substances. The attack may proceed without any external evidence of the injury which the mycelia are inflicting within the wood, or it may be proclaimed by the appearance of mushroom growths, termed "fruiting bodies," on the surfaces of the timbers. In either case, after a considerable proportion of the cell walls has been destroyed by the mycelia, the wood becomes brittle and weak. Decaying timber is further characterized by a lack of resonance when struck with a hammer, by an abnormal capacity for absorbing water, and very often by an unnatural odor and color.

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* See *Bull.* No. 219, Ohio Agric. Expt. Sta.

For life and propagation, fungi require air, moisture, warmth, and food supply. Not all fungi, however, thrive equally well under the same conditions. For example, the house fungus (*Merulius lachrymans*), Fig. 2, can live in air-seasoned timber surrounded by atmosphere with less than 70 per cent relative humidity, thrives at normal room temperatures, but is killed in an hour by a temperature of 115° F.* This fungus has been known to lie dormant for several years in a seasoned stick of timber. All that is required to revive it is an increase in the humidity of its habitat. Frequently the house fungus furnishes no surface indication of its presence. In such cases boring into beams or planks which are thought to be contaminated may reveal the extent of the rotting. Rotted timber forms brownish chips. If the fungus is alive its presence may be detected by cutting small cubes from the edges of the brown wood region. These should be soaked in a 2 per cent citric acid solution for about six hours; they should then be removed and stored in a closed jar at 75° F. for a couple of weeks. If filaments appear the fungus is alive. The insidiousness of the attack of the house fungus makes it most dangerous, especially in buildings of mill construction type. On account of the virility of the fungus under somewhat dry conditions, the name " dry rot " has been given to this form of decay.

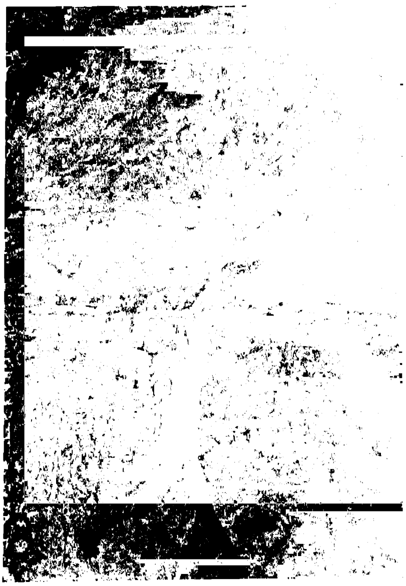
FIG. 2.—Strands of the House Fungus Found on Pine Planks at the Base of a Lumber Pile. (Photo by C. J. Humphrey.)

In contrast to the house fungus with its dry habitat and abnormal sensitiveness to heat, the following fungi which are characterized by many pores in their fruiting bodies may be mentioned: the *Fomes roseus, Trametes serialis* and the *Lenzites sepiaria*. The *Fomes roseus*, Fig. 3, has a hard pink fruiting body covered with small round pores; it lives in a saturated atmosphere and works much mischief to wood exposed in damp basements. The fruiting body of the *Trametes serialis*, Fig. 4, is tough; the surface is white and covered with small pores. It also works in a very moist atmosphere. The *Lenzites sepiaria* has a semi-circular plate-like fruiting body which has side attachment to the wood. The under side of its fruiting body is covered with gill-like pores. It is very active in destroying warehouse platforms and railroad ties. This fungus lives even when the temperature approaches the boiling point of water.

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* This discussion of the house fungus and dry rot is abstracted from a valuable article entitled "Dry Rot in Factory Timbers," by F. J. Hoxie, of the Inspection Dept. of Assoc. Factory Mutual Fire Ins. Co., Boston.

FIG. 3.—*Fomes Roseus* on the End of a Tie. (Photo by C. J. Humphrey.)

Certain fungi attack with avidity the products stored in the cell walls of the sapwood. This attack is most common in woods which are air-seasoned in a warm humid atmosphere. Despite the fact that no great damage to mechanical properties * appears to attend such action, at least in the early stages, yet the discoloration, which goes by the name of sap stain, is objectionable since it decreases the value of the timber.

204. Insects.—Although decay is the principal cause of deterioration of timber, an immense amount of damage is done annually by the attacks of insects. Timber with the bark on is especially liable to injury from them, and the attack once started in the green log may continue after the wood has been seasoned. Insects are particularly active in mine timbers, posts, poles, hickory hoops and poles, wagon stock, and pulpwood. Two common insects described by Weiss † are the powder-post insect and the pole-borer. Both of these insects evolve from small beetles. The powder-post variety comes from a small brown or black bug which, when out of doors, deposits its eggs early

FIG. 4.—*Trametes Serialis.* Upper specimen from under side of a floor, lower specimen from side of a girder. (Photo by C. J. Humphrey. Reduced about one-half.)

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* See tests in *Circular* No. 192 of Forest Service.

† See *The Preservation of Structural Timber*, Ch. II.

in the spring on the surface of the wood. The eggs hatch into a small white grub. The grub bores into the wood and transforms it into a fine powder while selecting its food. After a period of growth the worm forms a cavity in the wood and lies dormant while its legs and wings are being developed. Since this beetle multiplies very rapidly, the deterioration of the infested timber proceeds quickly.

The pole-borer comes from a reddish brown beetle about two-fifths to four-fifths of an inch long which deposits its eggs near the ground line of posts and poles during the late summer and early fall. On hatching, the creamy white grub bores into the wood. It transforms the wood tissue into a reddish brown or yellow dust which is packed into the burrow behind the worm. Like the powder-post insect, the pole-borer lies dormant in a cell in the wood until converted into a beetle. During the late summer the latter emerges from the pole through a large hole near the ground line. The pole-borer attacks both sound and decayed timber but is not active in the latter if it is water-soaked. It has been found in poles within two years after setting in the ground.

Termites, insects resembling white ants, have done a large amount of damage to wooden structures in the southern states and to a lesser extent in other portions of the country. The subterranean and dry-wood termites are the two classes operating in the United States. Both classes live very secretively in highly organized colonies and feed upon the cellulose in the wood without giving early external evidence of the damage being done. The subterranean variety inhabit dark, damp tunnels of properly regulated temperature well below the surface of the ground, and extend runways to the wood for food. The dry-wood termites do not require the humid earth habitat and, though less numerous, do much damage in the extreme south. Often the first warning of the presence of termites comes when a swarm of flying alates, young termites with wings, issues from an infested timber. These alates quickly lose their wings and die in large numbers, but the few survivors suffice to propagate new colonies.

Ravages of termites can be prevented by building tight concrete foundations, by keeping untreated timber out of contact with the ground, and by providing metal shields for all sills, foundation timbers, and conduits. Where termites have caused damage, badly infested members should be replaced by creosoted timbers. Timbers slightly damaged can be saved by treating with finely powdered Paris green or sodium fluosilicate.

205. Marine Borers.—There are two classes of marine borers infesting the waters of both Atlantic and Pacific Coasts, the mollusk and the crustacean types. Of the first class the teredo and xylotrya, which are very similar in appearance and mode of living, are the most important. Owing to their shape they are frequently called "shipworms." Either mollusk tunnels into the wood by means of a pair of shell valves and excretes the borings and a calcareous substance for lining the burrow through a posterior syphon. The food supply of the mollusk which consists of low forms of animal life found in the water, is secured through a second posterior syphon. The teredo rarely exceeds a length of 15 in. or a diameter of $\frac{3}{8}$ in., but specimens of xylotrya 6 ft. long by 1 in. in diameter have been reported. Shipworms infest warm salt water or brackish waters and are said to prefer calcareous shores. They attack piling between mean tide and the low water level; and at the Isthmus of Panama and along the coast of Florida have been known to ruin untreated timber in less than one year.

The limnoria or wood louse is the crustacean which is most dangerous to timber. It grows to the size of a grain of rice and bores into the wood by means of sharp jaws. It lives on food gotten from the wood substance which it penetrates radially to a depth of about $\frac{1}{2}$ in. per year. It is active only in clear salt water and confines its attack to a narrow belt around the piling near the low-water mark. The limnoria is particularly active in the Gulf of Mexico and along the north Pacific Coast.

No native timber except the palmetto appears to be highly resistant to the attack of marine borers. The greenheart of South America and the jarrah of Australia are also said to be highly resistant to such attack. Pine and fir are the timbers largely used for piling in this country, but they must be protected to withstand the ravages of these pests. Creosoting by the boiling or Bethell processes, or encasing the piling in concrete jackets are the methods of protection ordinarily used. Impregnation with creosote even when well done is not always proof against shipworms, while concrete casings are expensive and likely to be cracked. Borers in an attacked pile may be killed by chlorine gas, which is generated as follows: The pile is enclosed with a canvas curtain and an electric current passed through the pile and the enclosed salt water. The treatment is expensive and requires frequent repetitions in waters which are heavily infested with borers.

206. Other Deteriorating Influences.—Wood cross-ties, mine props and wharf timbers suffer considerably from mechanical wear. It is estimated that a tenth of the annual tie loss could be saved by the use of suitable tie-plates and improved spikes. It is not always possible or economical to protect timbers from mechanical wear, but in some cases iron plates may be effectively employed as shields.

Fire decomposes wood into carbon dioxide, water vapor and ash. Wet wood is about twice as resistant to fire as dry wood. Structural timbers which are well-seasoned will ignite with difficulty at temperatures in the vicinity of 400° F., and very quickly at temperatures around 600° F. Wood attacked by dry rot is more combustible than sound timber. Experiments by the National Fire Protection Association * show that the resistance of wood to fire can be much increased by saturating it with weak solutions (5 to 10 per cent) of ammonium sulphate or ammonium phosphate. Impregnation of the chemicals was accomplished by heating the solutions to 150° F. and maintaining a pressure of 130 lb. per square inch on the specimens for two hours while they were soaking. For wood exposed to moisture a treatment with zinc borate is effective. In this treatment the wood is first impregnated with a 10 per cent borax solution; it is then dried and again soaked in a 3 per cent zinc chloride solution. The two compounds react forming the insoluble borate which remains in the wood. The estimated cost of these treatments per thousand shingles ranged from $1.29 for the zinc borate treatment to $2.48 for a treatment with a solution of 4 per cent ammonium sulphate and 3 per cent ammonium phosphate. In view of the enormous annual fire loss in timber constructions, further experimentation along these lines should be done.

Woodpeckers do considerable injury to poles by boring into them and building their nests. Where the holes are well above the ground line, they cause little direct loss in strength or stiffness, but they afford excellent breeding grounds for fungi and thus may foster decay.

PRESERVATION

207. The Need of Preservation.—Statistics compiled by the Forest Service † show that the average life in years of untreated structural timbers in the United States is approximately as follows: Mine props, 3; piles, $3\frac{1}{2}$; ties, 7; posts, 8; lumber subject to decay, 8; poles, 13; and shingles, 18. Although statistics are not given, it is probable that between seventeen and twenty billion board feet of structural timber are used annually for replacements. Weiss estimates that the amount of timber cut for such purposes could be decreased annually by nearly seven billion board feet, if proper preservative methods were practiced. This would effect a net saving of not far from a hundred million dollars a year. From a consideration of the low durability of wood and the great cost of the quantity required for replacements, the need of practicing comparatively inexpensive methods of preservation becomes evident. Furthermore, the proper use of efficient protectives would lead to the planting of more rapidly growing trees, the more effective utilization of inferior trees and top logs, the clearing of land occupied by fire-killed timber (since the latter can be effectively used if treated); in short preservation would lead to better forest management in general.

In 1937 about four-fifths of the cross-ties, a like proportion of the poles, and a small proportion of the piling, building, and bridge timbers annually used in the United States were given a preservative treatment. The entire amount of timber treated in this country in a year is approximately 200,000,000 cubic feet. To treat this amount of wood about 150,000,000 gallons of creosote, 20,000,000 gallons of petroleum, about 4,000,000 pounds of zinc chloride, and a million pounds of various salts are consumed.

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* Rept. of Common Uses of Wood in *Proceedings* of 1915.

† See *Bulletin* 78.

208. The Relations of Structure to the Penetrance of Preservatives.—Structure plays a very important role in determining the ease with which preservatives may be forced into wood and also in fixing the quantity injected. In most woods the sapwood is more easily impregnated and absorbs more preservative than the heartwood. However, in hemlock, alpine fir, and white spruce the sapwood is scarcely less resistant to penetration than the heartwood. Bark is nearly impenetrable and should always be completely removed from timber which is to be treated. The comparative resistance of the heart and sapwood should be considered in forming timbers which are to be treated. In the diffuse-porous woods and in those conifers which show little demarkation between spring and summer wood, the absorption of preservative is more uniform than in the ring-porous hardwoods or the hard pines. In the ring-porous woods most of the preservative will run into the spring wood, whereas in longleaf pine the greater part will be found in the dense summer wood. Owing to the difference in the absorption of preservative by the spring and summer wood of the hard pines, a minimum limit on the number of rings per inch is often placed in specifications. The purpose of this restriction on rate of growth is to prevent wide variations in the distribution of the preservative.

Within a given species it is likely that the absorption of preservative varies inversely as the density of the wood, but no such relation exists between timbers of different species. Thus, red oak and hard pine, which are comparatively heavy woods, absorb much more preservative than the light white spruce.

Since nearly all of the preservative is held in the cell cavities and only a small proportion permeates the cell walls, it follows that any condition which causes a plugging of these cells will interfere with the injection of preservatives. Such conditions are effected in many woods by tyloses (Art. 197, 198 and 199). If such woods are treated, the preservative is likely to be very non-uniformly distributed.

In coniferous wood the resin-ducts, if unclogged by resin or growths, serve as canals for the rapid passage of preservatives. It is probable that the great absorption of the dense summer wood of the hard pines is due to the fact that it contains these ducts. Nearly all of the pines also possess radial resin-ducts which materially assist in the radial penetration of preservatives. Radial ducts are lacking in the larches, hemlocks, firs and spruces; and it is much more difficult to secure a deep radial penetration in them than in the pines.

In some woods it is probable that the radial transmission of preservatives is affected through pit membranes in the cell walls. Tiemann and Weiss claim that slits which are opened in the cell walls during seasoning are another possible avenue of transmission.

Besides these physical characteristics of the wood structure, the chemical composition of the cell walls probably has an important influence on the absorption of preservatives.

Among the woods which are most readily injected with preservatives are longleaf pine, shortleaf pine, Western yellow pine, lodgepole pine, loblolly pine, red birch, white elm, red elm, soft maple, beech and red oak. White oak, alpine fir, Douglas fir, tamarack and white spruce are treated with difficulty. In this connection it should be recognized that the form of the timber often plays an important part in determining the penetration of preservation. For example, a Douglas fir pole can be easily impregnated with preservative because of its sapwood envelope. On the other hand, a large dimension timber of this species having considerable exposed heartwood would be treated with much difficulty on account of the resistance of the heartwood to penetration.

209. The Treatment of Timber before Preservation.—Timber is best cut in the fall or winter to avoid fungus or insect attack and to prevent checking produced by too rapid drying. Bark should be promptly removed from logs to prevent insect and fungus attack. Such procedure also renders the timber more permeable to preservatives. Too rapid seasoning after bark removal should be avoided, since it causes case hardening and thus increases resistance to penetration of preservatives.

Penetration of preservatives into woods lacking open radial ducts like fir, larch, maple, and birch is materially improved by incising timbers by toothed rolls to a depth of a half to three-fourths of an inch. The use of this treatment is growing rapidly.

It is desirable that all timber which is to be treated be thoroughly seasoned in order that the penetration of preservatives may be facilitated. With the exception of air-seasoning, exposure to saturated steam is the most-used conditioning process for timber which is to be preserved. Under this process the timber is placed in a large treating cylinder and subjected to live steam at a pressure of 20 to 40 lb. per square inch for two to ten hours, the time being dependent on the size and character of the timber. A vacuum of about 25 in. is then applied for thirty minutes to two hours, after which the timber is treated with preservative. This process is a preliminary stage in several of the common methods of treatment. With a few creosoting processes, seasoning is accomplished by running the timber into a cylinder and soaking it in creosote. The oil is gradually heated until the temperature is raised above the boiling-point of water. This causes the latter to vaporize. The vapor is drawn off and condensed to free it of oil. After the moisture in wood has been sufficiently reduced, the cylinder is filled full of preservative and pressure is applied until impregnation is completed.

Superficial Treatments

210. Conditions for Use of Superficial Treatments.—There are three inexpensive methods of treating the surface of timber to protect it against decay and insects. These methods are of value when the amount of timber to be treated is too small to warrant the erection of a treating plant; when it is impracticable to haul the timber to the work from a plant; or when it is necessary to do the work at a minimum cost. Since the value of every one of them is based upon the maintenance of an unbroken film which will resist the attack of fungi, it is very necessary that the timber shall be thoroughly air-seasoned before treating. If the timber is only partially seasoned or green when treated, it is likely to check subsequently and thus produce passage ways for insects and mycelia.

211. Brush Treatments.—Probably the most-used superficial treatments are those in which a liquid is applied to the surface of the timber by means of a brush. Creosote, paint, oil, and whitewash are among the liquids used for the purpose. Creosote should be heated to about 200° F. before applying to the wood, since heating considerably decreases the viscosity of the oil and thereby aids in securing penetration of the preservative. Great pains should be taken to thoroughly coat all defects and fill checks, shakes and joints. This method of treatment has been used considerably for the preservation of mine timbers, poles and posts. It is well adapted to use on farms.

212. Dipping.—By dipping the timber into the preservative and allowing it to soak for a few minutes, it is possible to secure a more complete coating of the defects than is gotten by brush treatments. The process requires the use of a large tank for holding the timber and necessitates a somewhat greater use of preservative, but the labor cost is less than in the brush process. It can be very effectively used for butt treatments on fence posts and poles. When used for this purpose the preservative should cover the pole for at least a foot above the ground line.

213. Charring.—A very old and inexpensive method for protecting wood consists in charring the outer fibers of the timbers by fire. This process produces an envelope of charcoal which, being devoid of food elements, is not attacked by fungi. If the strength of the pieces treated is of great importance this process is detrimental, because it destroys the outer fibers and injures those immediately beneath. It has been used for treating the butts of posts and poles, but is not very efficacious.

NON-PRESSURE PROCESSES OF IMPREGNATION

214. The Value of Non-pressure Processes.—In the non-pressure processes the preservative is drawn into the wood by absorption or it is forced in by atmospheric pressure. By these processes it is not possible to secure as uniform and deep penetrations as with the pressure methods, but with woods like loblolly pine, shortleaf pine, red cedar and beech, they can be successfully used. These processes require a longer time for treatment than the pressure processes. On the other hand, since they use no heavy treating cylinder with its expensive equipment, they afford cheap and effective means of preserving small quantities of poles, mine timbers and ties, provided the wood is easily impregnated. The method is also of value when salts which would attack iron treating cylinders are used.

215. Open-tank Process.—In this treatment the timber is placed in a tank and covered with the preservative. The charge is then heated to a temperature just above the boiling point of water. This serves to expel a considerable proportion of air and moisture from the cells in the wood. After soaking at this temperature for an hour or two the timber may be allowed to cool with the liquid, or it may be transferred to a cold tank where it is kept for another hour or more depending on how deep a penetration is wanted. As the wood cools a vacuum is formed in the outer cells and the preservative is injected by atmospheric pressure. Sometimes, when a deep penetration is desired with a minimum expenditure of preservative, the timber is drawn from the cooling tank before it has entirely cooled. As the interior of the stick gradually cools vacuums are formed which are filled by the excess fluid held in the outer cells.

The process may be used with creosote, zinc chloride, or crude oil. However, if the wood is boiled in the zinc chloride solution, its strength is likely to be impaired.

216. Kyanizing.—In this process the timber, which must be thoroughly seasoned, is immersed in a 1 per cent solution of bichloride of mercury for a number of days. The time of treatment is dependent upon the thickness of the pieces and the depth of penetration desired. Ordinarily the time in days is equal to the thickness of the timber in inches plus one, and the depth of penetration does not exceed a quarter of an inch. Owing to the poisonous character of the salt great care must be exercised during the treatment of the timber; and the treated lumber should not be used where it is likely to be licked by animals.

As a means of preserving timber used in dry locations, this process ranks high; but on account of the poisonous nature of the salt, the long time required for the process, and the solubility of the salt in water, it has not been widely used in this country.

PRESSURE PROCESSES OF IMPREGNATION

217. *Field of Use.*—In general the pressure processes are the most satisfactory methods of treating large amounts of timber. Furthermore, these methods are the only ones which can be successfully used to impregnate many kinds of wood, such as hemlock, Douglas fir and redwood.

218. Bethell or Full-cell Process.—The timber for treatment is placed on small cars and carried into horizontal steel cylinders which are ordinarily about 130 ft. long by 7 ft. in diameter. A vacuum is drawn to remove air from the cylinder and from the wood. Coal-tar creosote oil, heated to proper temperature, is then admitted to the cylinder and forced into the timber by a pressure of 100 to 180 lb. per square inch. The pressure is maintained until the oil gages show the required impregnation. Then the oil is blown out of the cylinder into reservoirs, and the timber, after dripping for a few moments, is removed. In some plants dripping is accelerated by drawing a vacuum just before removing the timber. The process is much used both in this country and abroad. It is especially valuable for wood-block and piling where a heavy impregnation of oil is imperative. On account of the large expenditure of oil, 10 to 20 lb. per cubic foot, the process is very costly. The cost of treating cross-ties by it ordinarily runs between 75 cents and one dollar each.

219. Burnettizing.—This process is performed in the same manner as the Bethell process, but differs in the preservative. An aqueous solution containing from 2 to 5 per cent of zinc chloride is used and about ½ lb. of salt per cubic foot is the average impregnation in the process. Owing to the solubility of zinc chloride in water, the process is not suited to treating timbers which are to be placed in damp locations. It is a very inexpensive process costing about one-third as much as the full-cell treatment. Burnettizing has been successfully used to treat ties and lumber both in the United States and in Europe.

220. The Boiling Process.—In this process either green or seasoned timber is given a conditioning treatment in creosote oil (see Art. 209) before impregnation with creosote. After the oil conditioning the remainder of the process is much like the Bethell method. The boiling method is used principally in preserving Douglas fir. Tests indicate that it may injure the strength of this wood. (Art. 243.)

221. The Rueping Process.—One of the most important processes both here and abroad is the Rueping empty-cell process with creosote. Air-seasoned timber is preferred, although steam-treated material can be used. After placement in the treating cylinder, the cells of the wood are filled with compressed air which is admitted under a pressure of about 75 lb. per square inch. Oil is then admitted at a slightly higher pressure until the wood has been immersed, when the pressure is raised to 150 lb.

per square inch or more. After the proper amount of oil has been injected, the creosote is forced out of the cylinder and the pressure released. As the pressure is withdrawn the compressed air within the wood expels the excess oil into the cylinder. It is thus possible to secure a deep penetration and to coat the cell walls with 5 to 7 lb. of oil per cubic foot of wood. Treatments by this process cost about two-thirds as much as the full-cell methods.

222. The Lowry Process.—This process, like the Rueping, is planned to secure a deep penetration of oil with a small absorption. Air-dry timber is run into the cylinder and submerged in creosote oil at a temperature of about 200° F. Pressure is then applied, and the temperature and pressure are regulated until the timber has been filled with oil. After withdrawal of the oil a vacuum is drawn until the surplus oil in the wood cells has been removed. When the excess oil has been removed from the cylinder, the timber is taken out. The process is somewhat more expensive than the Rueping process but less costly than the full-cell. It is considerably used in the United States for treating cross-ties.

223. The Card Process.—Owing to the high cost of creosote oil and the solubility of zinc chloride neither of these preservatives has been universally adopted. The aim of the Card process is to lessen these objectionable features by using a mixture of 15 to 20 per cent of creosote with a 3 to 5 per cent solution of zinc chloride. In operating the process, air-seasoned timber is run into the treating cylinder and given a vacuum treatment for about an hour. It is next immersed in the preservative at a temperature of about 180° F. A pressure of approximately 125 lb. per square inch is then applied for several hours. During this period the mixture of oil and zinc chloride is stirred continuously by a centrifugal pump to prevent separation of the components. After impregnation has been finished, the preservative is drained from the cylinder, and a vacuum drawn to remove surplus preservatives from the wood cells. By the Card method approximately as much zinc chloride is injected as in Burnettizing together with about 3 to 5 lb. of creosote per cubic foot. The process costs about one half as much as the Bethell process and has found favor in this country for the treatment of cross-ties.

PRESERVATIVES AND THE EFFICIENCY OF PRESERVATION

224. Preservatives.—Inasmuch as fungi cannot thrive without moisture, waterproofing of seasoned wood will render it resistant to attack. Crude oil, paint and stains are the common preservatives of this class. A far surer treatment is effected, however, by preservatives which poison the food supply of fungi and insects. The creosote oils and the inorganic salts,—zinc chloride, mercuric chloride and copper sulphate,—are members of the latter class.

The term crude oil includes three classes, (1) oil with a paraffin base,

(2) oil with an asphaltic base, and (3) the product which is left after the lighter oils are distilled from crude oil called residuum. These oils are all lighter than water but penetrate coniferous wood less readily than creosote. For successful treatment with them, the timber must be fully impregnated, thus rendering it heavy and likely to drip. The cost of sufficient oil to treat a cubic foot of timber runs from 3 to 7 cents. Crude oil is used but little in the United States.

Most of the paints used to protect wood consist of linseed oil, turpentine and some inorganic coloring material. Although fungi will not attack a painted surface, most paint cannot be classed as an effective preservative when the wood is in contact with the soil, since it is somewhat porous and permits the passage of moisture. Stains having a creosote base with a vegetable or mineral-oil body are poisonous to fungi. They also penetrate further into the wood than do the paints, but are more volatile.

Creosote oils of three varieties are used in wood preservation; coal-tar creosote, water-gas-tar creosote, and wood-tar creosote. They are all tar distillates and are very poisonous to fungi and insects. However, the volatile nature of the lighter fractions of these oils, their pungent odor and the fact that they increase the inflammability of wood render them unsatisfactory for some purposes. Creosote is also an expensive preservative; the cost ranges from 5 to 15 cents per cubic foot of treated wood, depending on the price of oil and the process used. Nevertheless, in spite of these objectionable features approximately two-thirds of the timber annually treated in the United States is impregnated with coal-tar creosote.

Coal-tar creosote is a complex oil resulting from a double distillation of coal. In the first distillation the products are coke, gas, and tar. If the tar is again distilled three classes of compounds are formed—pitch, oils lighter than water, and oils heavier than water. The latter are the creosotes. They consist principally of phenols, naphthalene and anthracene. Tests made at the Forest Products Laboratory show that from 0.2 to 0.4 per cent of this oil in a culture medium is sufficient to kill fungi. For methods of sampling and analyzing creosote oil, see current *A.S.T.M. Standards*.

Water-gas tar is a by-product from the manufacture of water gas. By passing steam through red-hot coke or coal it is decomposed and hydrogen, carbon monoxide, carbon dioxide, and methane are formed. These gases are then passed through a heated carburetter into which a spray of crude petroleum is simultaneously admitted. Gas and tar are thus evolved. By distillation the tar is separated into three components, oils lighter than water, pitch, and the creosote oils which are heavier than water. Very little water-gas tar creosote is used as such for preservative purposes, but it is sometimes used as an adulterant of coal-tar creosote. It is probably no more volatile than the coal-tar product, but is less deadly to fungi.

Wood-tar creosote is derived from treble distillation of resinous woods. Owing to the expense of this oil its use has been largely confined to the manufacture of stains and patented coatings.

The inorganic salts which are used for wood preservation are all highly toxic to fungi. They are also non-volatile and odorless. Furthermore, timber into which these salts are injected can be covered with paint, whereas creosoted timber is coated with great difficulty. On the other hand, these salts are soluble in water and are likely to leach out of the timber if it is exposed to moisture.

Zinc chloride is the most important of the inorganic salts. It is equal in toxicity to coal-tar creosote but corrodes the iron-treating cylinders to a slight extent. It is a very cheap preservative costing about 5 cents a pound or 2 to 3 cents per cubic foot of treated timber. About one-fourth of the timber treated in this country is injected with zinc chloride.

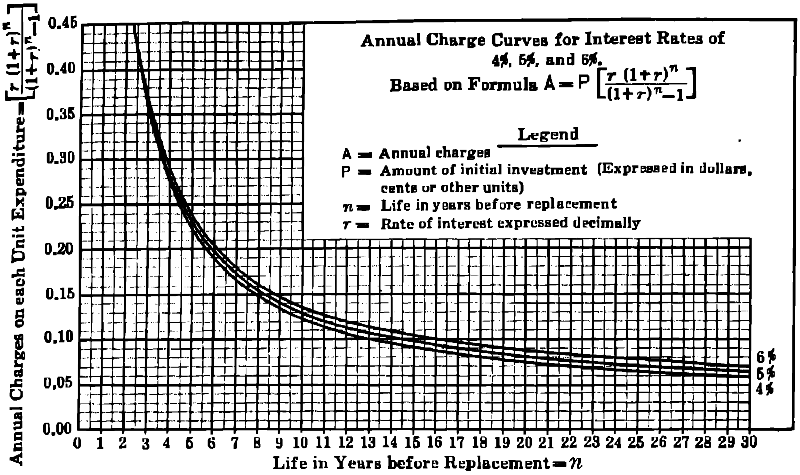
Mercuric chloride is the most toxic preservative and on this account is often a menace to the users of the treated timber. It is less soluble in water than zinc chloride but much more corrosive to iron. From records it appears to confer a somewhat longer life on treated timber. The cost of mercuric chloride per cubic foot of treated timber is about the same as that of zinc chloride.

Copper sulphate is a preservative of high toxicity, but readily leaches from the timber. It is fairly cheap and appears to be about as efficient a preservative as zinc chloride. The depth of penetration is readily determined by the blue stain which the liquid imparts to the wood. Since it attacks iron with great vigor, it cannot be used with the ordinary treating apparatus. The largest use of this preservative is made in France.

225. Economy in Preservation.—Economy is effected by preservative treatment whenever the annual charge against the treated timber is less than the annual charge against any untreated timber (or other material), which would serve the purpose. To illustrate the economy of timber preservation, examples applying to Table 1 and Fig. 5 are included.

TABLE 1.—ESTIMATED LIFE OF TREATED AND UNTREATED CROSS-TIES IN YEARS

	Redwood	Cedar	Cypress	White Oak	Longleaf Pine	Douglas Fir	Western Larch	Tamarack	Western Hemlock	Chestnut	Red Oak	Beech	Birch	Maple	Lodgepole Pine	Western Pine	Loblolly Pine	Red Gum
Untreated	12	11	10	8	7	7	7	5	5	5	4	4	4	4	4	4	3	3
10 lb. creosote per cubic foot	. .	. .	. .	. .	20	15	15	15	15	12	20	20	20	18	15	15	15	16
½ lb. zinc chloride per cubic foot	. .	. .	. .	. .	11	11	11	11	11	9	12	12	12	12	11	11	10	11



By Courtesy of Forest Products Laboratory.

FIG. 5.

The estimated lives of ties given in this table were largely prepared from data furnished by Mr. C. H. Teesdale, of the Forest Service. The formula of Fig. 5 gives the amount which must be invested each year at a given rate of compound interest to provide a sum which, when the tie or other unit is worn out, will equal the first cost of the tie plus the interest charges.

Example: A lodgepole pine tie costs approximately one dollar. The 10 lb./cu. ft. creosote treatment costs about 80 cents per tie and the ½ lb./cu. ft. zinc chloride treatment may cost 20 cents per tie.

(*a*) Untreated: Cost of tie and placement		$1.50
Table 1, approximate life	4 years	
Fig. 5, annual charge per unit	0.28	
Therefore annual charge is	$1.50×0.28 =	$0.42
(*b*) Treated with 10 lb./cu. ft. creosote:		
Cost of tie and placement		$1.50
Cost of treatment		0.80
Total cost		$2.30
Table 1, approximate life	15 years	
Fig. 5, annual charge per unit	0.10	
Therefore annual charge is	$2.30×0.10 =	$0.23
(*c*) Treated with ½ lb./cu. ft. zinc chloride:		
Cost of tie and placement		$1.50
Cost of treatment		.20
Total cost		$1.70
Table 1, approximate life	11 years	
Fig. 5, annual charge per unit	0.128	
Therefore annual charge is	$1.70×0.128 =	$0.22

These examples demonstrate the method of computing the annual charge and emphasize the great saving accomplished by preservation of non-durable timbers.

CHAPTER VI

THE MECHANICAL PROPERTIES OF TIMBER

226. Introduction.—In order that the engineer may properly design columns and beams for various parts of wooden structures, he must be thoroughly conversant with the strength and stiffness of the available classes of timber. He must also know how various defects and conditions influence these properties. The architect must not only appreciate the beauty of the various species, the relative ease with which each may be worked, the tendency to shrink, warp and check; but he must likewise be prepared to proportion joists and rafters to carry the imposed loads without excessive deflection. The wheelwright must understand how the toughness and strength of his axles, spokes, and shafts are influenced by species, rate of growth, density, and defects. The carpenter and the craftsman must also have knowledge of the mechanical properties of wood in order that they may work it to best advantage.

Furthermore, wood of a given species is extremely variable. Trees differ markedly in their rate of growth, due to climatic conditions, the density of the surrounding forest, the character of the soil and the physiography of the region in which they grow. These conditions of growth, the position in the tree, the amount of moisture and the defects all influence the mechanical properties of a piece of timber of a given species.

Recognizing the importance of a knowledge of the properties of wood and the factors influencing them, Dr. B. E. Fernow, chief of the Forestry Division of the U. S. Agricultural Department, inaugurated a series of timber tests in 1891. In the beginning, the microscopic and physical tests were conducted at Washington and the mechanical tests were made by J. B. Johnson, at Washington University, St. Louis. Later the mechanical tests were distributed among a number of technical laboratories in various parts of the country. In 1909 the major portion of the work done at the various laboratories was transferred to the Forest Products Laboratory * at Madison, Wis.

Mechanical tests of timber are only a portion of the work carried on at this laboratory. Studies of the physical and chemical properties, the microscopic structure, the methods of preservation of wood, and the utilization of wood products are among the other more important lines of investigation being conducted by this institution.

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* This laboratory is run by the U. S. Government in cooperation with the University of Wisconsin.

On account of the broad scope of these investigations, the great pains which are taken to identify species, to select properly both specimens and trees, and on account of the care taken to eliminate variables in testing, the results obtained are of very great value. Most of the data in this chapter are taken from publications of this laboratory. The *Wood Handbook* prepared by the laboratory contains much additional valuable information.

The mechanical tests which are most commonly made at the Forest Products Laboratory are: compression, shear, both static and impact bending, tension, hardness, and cleavage. Observations are also made on the number of rings per inch, percentage of summer wood, percentage of moisture, density, and shrinkage. The more important conditions pertaining to the methods of testing wood considered in Ch. III are supplemented, when necessary, in the discussions on mechanical properties which follow.

THE STRENGTH OF WOOD

227. Compressive Strength.—When wood is subjected to compressive forces acting parallel to the axis of growth (parallel to the grain), it is, in proportion to its weight, one of the strongest of structural materials. Columns and posts are, therefore, often fashioned of it. Inasmuch as the strength of such a member is a function of the compressive strength and the slenderness ratio, information concerning the former is of much importance. Furthermore, a knowledge of the compressive strength is of value in estimating strength in bending, since experiments have demonstrated that the yield point of a wooden beam is determined by the compressive strength of the wood. The compression test is not, however. as effective in demonstrating the weakening influences of defects as the cross-bending test.

When wood is subjected to compression parallel to the grain it may fail through collapsing of the cell walls or through lateral bending of the cells and fibers. In most of the conifers where the cells (tracheids) have thin walls, failure begins at pits in the walls of one of these cells and gradually causes a collapse of the entire cell. The plane of rupture is generally inclined about 60° to 75° with the axis of the cell. From the inclination of the plane of failure it appears probable that final collapse is due to the weakness of the cell wall in transverse shear. Adjacent cells are overstressed by the failure of the individual cell and a wrinkling of the surface, showing the progress of the breakdown throughout the specimen, becomes visible. In wet wood and in the hardwoods, which are composed of thick-walled fibers and vessels, incipient failure is due to bending of the individual fibers. Occasionally after the wrinkling begins, the specimen is separated into groups of fibers by longitudinal cracks. This condition is brought about by splitting of the fibers and not by failure of the bond

between fibers.* It will be generally noted that the line of failure on tangential surfaces of the specimen is inclined as previously stated; but on radial surfaces it is approximately normal to the axis of the test-piece. The direction in the latter case is much influenced by the medullary rays. In cross-grained pieces the failure is likely to take place through shear parallel to the grain.

The strength of timber compressed across the grain is brought into play wherever a concentrated load is imposed on a beam. Since the compressive strength across the grain is only a small fraction of the compressive strength parallel to the grain, proper allowance for this discrepancy must be made in designing columns resting on wooden beams or the column must be provided with a footing, to distribute the pressure.

Tests on compression across the grain are often made with the pressure distributed over only part of one of the loaded surfaces. Thus for tests on small specimens at the Forest Products Laboratory, a 2×2×6-in. block is used and loads are applied over the lower 2×6-in. surface and the middle third of the upper surface. Although such procedure does not give the true cross-grained compressive strength, it more nearly approaches the loading condition ordinarily met in a structure. In such tests, as the load is increased, the upper bearing closes the cell cavities immediately beneath it and gradually indents the surface. Beam action in the upper fibers often produces splitting in planes perpendicular to the line of pressure, but there is no well-marked failure.

Strictly speaking, timber does not have a well-defined elastic limit, since it takes set after the imposition of low loads. Nevertheless, the initial portion of the stress-deformation curve is approximately straight and it has become customary to record the stress corresponding to the limit of proportionality as the elastic limit. This is the only value of importance in tests across the grain.

Values of the compressive strengths of 2×2-in. prisms of 85 woods in green condition appear in Table 1. In Table 2, similar values may be found for larger sizes of the common structural timbers when air-seasoned. Table 3 shows the relation of air-seasoned to green material. Among the species having greatest compressive strength parallel to the grain we note locust, blue gum, hickory, white or green ash, walnut, yew, Cuban and longleaf pine, and lowland Spanish oak. The strongest structural timbers are oak, maple, bald cypress, Douglas fir, western larch, and the southern yellow pines.

For most of the conifers the compressive elastic limit across the grain varies between 12 and 18 per cent of the values determined for pressures parallel to the grain. Among the hardwoods the elastic limit in compression across the grain bears a higher ratio to the strength in compression parallel to the grain, the ratio being about 25 per cent for several

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* Record, *Mechanical Properties of Wood*, p. 15. (Out of print.)

TABLE 1.—RESULTS OF TESTS ON 85 SPECIES OF WOOD TESTED IN A GREEN CONDITION IN THE FORM OF SMALL CLEAR PIECES

From Bulletin No. 556 U. S. Dept. of Agriculture

[Test specimens are 2 by 2 inches in section. Bending specimens are cut 30 inches long; others are shorter, depending on kind of test.]

Common Name	Locality Where Grown					Specific Gravity, Oven Dry, Based on—			Shrinkage from Green to Oven-dry Condition			Static Bending					Impact Bending			Compression Parallel to Grain					Hardness, Load Required to Imbed a 0.444-Inch Ball to One-half Its Diameter	
															Work in Bending—											
		Number of Trees Tested.	Number of Rings per Inch.	Summerwood (Per Cent).	Moisture Content (Per Cent).	Volume When Green.	Volume When Oven-dry.	Weight per Cubic Foot (Green) (Pounds).	In Volume (Per Cent of Dimensions When Green)	Radial (Per Cent of Dimensions When Green).	Tagential (Per Cent of Dimensions When Green).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Modulus of Rupture (Pounds per Square Inch).	Modulus of Elasticity (1000 Pounds per Square Inch).	To Elastic Limit (Inch-pounds per Cubic Inch).	To Maximum Load (Inch-pounds per Cubic Inch).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Work in Bending to Elastic Limit (Inch-pounds per Cubic Inch).	Height of Drop Causing Complete Failure, 50-pound Hammer (Inches).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Maximum Crushing Strength (Pounds per Square Inch).	Compression Perpendicular to Grain—Fiber Stress at Elastic Limit (Pounds per Square Inch).	Shearing Strength Parallel to Grain (Pounds per Square Inch).	Tension Perpendicular to Grain (Pounds per Square Inch).	End (Pounds).	Side (Pounds).
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
HARDWOODS																										
Ash, black.	Mich., Wis.	15	24	53	83	0.46	0.53	53	15.2	5.0	7.8	2600	6,000	1020	0.42	12.4	7,200	2.5	32	1620	2,290	430	870	490	580	550
Ash, green........	Mo., La.	10	18	58	48	.52	.61	48	12.5	4.6	7.1	5300	9,500	1400	1.14	11.8	11,400	5.0	34	3560	4,200	910	1260	590	960	870
Ash, white (forest grown).........	Ark., W.Va.	10	16	50	43	.52	.60	46	12.6	4.2	6.5	4900	9,100	1350	1.03	13.4	11,700	5.0	36	3230	3,800	800	1260	620	1000	900
Ash, white (second growth)........	N. Y.	5	9	63	40	.58	.71	51	14.0	5.3	8.7	6100	10,800	1640	1.30	16.3	13,800	5.9	47	3820	4,610	790	1600	790	1140	1080
Aspen...........	Wis.	5	8	...	107	.36	.42	47	11.1	3.3	6.9	2900	5,300	840	.65	6.9	6,900	2.5	28	1620	2,160	200	620	180	270	320
Basswood........	Penn., Wis.	8	19	29	103	.33	.40	41	15.8	6.6	9.3	2700	5,000	1030	.42	5.2	6,200	2.0	17	1710	2,210	210	610	280	280	250
Beech...........	Ind., Penn.	10	19	30	62	.54	.66	55	16.2	4.8	10.6	4500	8,200	1240	.99	12.5	10,400	4.2	40	2550	3,280	610	1210	760	950	820

Birch, paper......	Wis.	5	6	30	72	.47	.60	51	16.3	6.6	8.8	2900	5,800	1010	.49	15.0	7,800	2.7	45	1650	2,210	300	790	380	400	490
Birch, yellow......	Penn., Wis.	10	19	26	68	.54	.66	58	16.8	7.4	9.0	4600	8,600	1540	.80	16.6	11,700	4.5	40	276	3,460	450	1110	480	820	740
Butternut........	Tenn., Wis.	10	9	...	104	.36	.40	46	10.2	3.3	6.1	2900	5,400	970	.52	8.2	7,300	2.5	24	1960	2,420	270	760	430	410	390
Chestnut.........	Md., Tenn.	10	10	48	122	.40	.46	55	11.6	3.4	6.7	3100	5,600	930	.59	7.0	7,900	2.8	24	2040	2,470	380	800	430	530	420
Cottonwood......	Mo.	5	6	...	111	.37	.43	49	14.1	3.9	9.2	2900	5,300	1010	.40	7.3	7,200	2.3	21	1770	2,280	240	680	410	380	340
Cottonwood, black.	Wash.	5	6	...	132	.32	.37	46	12.4	3.6	8.6	2900	1,800	1070	.44	5.0	6,800	2.2	20	1770	2,160	200	600	270	280	250
Elm, cork........	Wis.	10	28	50	50	.58	.66	54	14.1	4.8	8.1	4600	9,500	1190	1.20	19.8	11,000	4.1	50	2870	3,780	750	1270	660	980	990
Elm, slippery.....	Ind., Wis.	6	16	54	85	.48	.56	56	13.8	4.9	8.9	4000	8,000	1230	.32	15.4	9,200	3.4	47	2840	3,320	510	1110	650	750	660
Elm, white.......	Wis., Penn.	6	18	31	88	.44	.54	52	14.4	4.2	9.5	3600	6,900	1030	.33	11.0	8,100	2.9	34	2290	2,880	390	920	560	610	550
Gum, black.......	Tenn.	5	27	...	55	.40	.55	45	13.9	4.4	7.7	4000	7,000	1030	.91	8.0	9,800	4.0	30	2440	3,040	600	1100	570	790	640
Gum, blue........	Cal.	5	...	...	79	.62	.80	70	22.5	7.6	15.3	7600	11,200	2010	1.65	13.9	14,200	4.7	40	4870	5,250	1020	1550	640	1310	1340
Gum, Tupelo......	La.	6	10	26	97	.46	.52	58	12.5	4.2	7.6	4200	7,300	1050	.98	6.3	9,000	3.3	30	2760	3,370	590	1190	600	800	710
Gum, red.........	Mo.	10	16	...	81	.44	.53	50	15.0	5.2	9.9	3700	6,800	1150	.81	9.4	10,000	3.9	33	2360	2,840	460	1070	510	630	520
Hickory, big shellbark...........	Miss., O.	19	19	65	61	.62	....	63	19.2	7.6	12.6	5600	10,500	1340	1.36	29.9	14,200	7.0	104	2740	3,920	1000	1190	....	....	....
Hickory, bitternut.	O.	11	11	70	66	.60	....	63	....	....	....	5500	10,300	1400	1.22	20.0	15,900	8.5	66	4330	4,570	990	1240	....	....	....
Hickory, mockernut	W. Va., Miss., Penn.	20	18	63	59	.64	....	64	17.9	7.8	11.0	6300	11,100	1570	1.38	26.1	15,100	6.7	88	3900	4,480	1000	1280	....	....	....
Hickory, pignut...	O., Miss., Penn., W. Va.	60	20	65	54	.66	....	64	17.9	7.2	11.5	6200	11,700	1650	1.34	31.7	16,900	8.8	89	3950	4,810	1140	1370	....	....	....
Hickory, shagbark.	....do....	24	19	66	60	.64	....	64	16.7	7.0	10.5	5900	11,000	1570	1.28	23.7	14,400	6.4	74	3430	4,580	1000	1320	....	....	....
Locust, black.....	Tenn.	3	11	51	40	.66	.71	58	9.8	4.4	6.9	8800	13,800	1550	2.36	15.4	18,300	7.9	44	6280	6,800	1430	1760	770	1640	1570
Locust, honey.....	Mo., Ind.	6	9	45	63	.60	.67	61	10.8	4.2	6.6	5600	10,200	1290	1.40	12.6	11,800	4.6	47	3320	4,420	1420	1660	930	1440	1390
Maple, Oregon....	Wash.	5	12	...	72	.44	.51	47	11.6	3.7	7.1	4400	7,400	1100	1.02	8.7	8,500	2.8	23	2380	3,240	550	1110	600	760	620
Maple, red.......	Penn., Wis.	9	16	24	70	.48	.54	51	12.5	3.8	8.1	4100	7,800	1420	.60	10.[illegible]	9,000	3.7	30	2500	3,350	520	1080	580	710	600
Maple, silver......	Wis.	5	7	...	66	.44	.51	46	12.0	3.0	7.2	3100	5,800	940	.61	11.0	6,800	2.6	29	1950	2,490	460	1050	560	670	590
Maple, sugar......	Ind., Penn., Wis.	17	21	49	60	.56	.66	56	14.5	4.8	9.2	5000	9,100	1480	1.08	11.[illegible]	12,100	5.0	36	3120	3,860	750	1380	770	1000	910
Oak, bur.........	Wis.	5	12	59	70	.58	.67	61	12.7	4.4	8.8	3600	7,200	880	.89	10.7	10,000	4.7	44	2310	3,290	840	1350	800	1160	1110
Oak, California black..........	Cal., Ore.	10	16	52	106	.51	.58	66	12.1	3.6	6.6	3400	6,200	740	1.03	8.8	8,200	3.4	30	1880	2,800	890	1140	700	910	850
Oak, chestnut.....	Tenn.	5	23	50	72	.57	.67	62	16.7	5.5	9.7	4600	8,000	1370	.90	9.4	12,000	4.6	35	2890	3,520	660	1210	690	970	890
Oak, Pacific post..	Ore.	10	16	49	72	.64	.75	69	13.4	4.2	9.0	4600	7,700	790	1.51	13.7	10,300	4.8	49	2510	3,570	1380	1630	940	1430	1390
Oak, post.........	Ark., La.	10	26	54	69	.60	.74	63	16.2	5.4	9.8	5000	8,100	1090	1.31	11.0	10,900	4.1	44	2840	3,480	1060	1280	790	1160	1130
Oak, red..........	Ark., La., Ind., Tenn.	21	11	62	84	.56	.65	64	14.2	3.9	8.3	3700	7,700	1290	.65	11.5	10,400	3.9	41	2330	3,200	730	1120	740	1020	950
Oak, Spanish (highland)...........	La.	4	20	46	90	.52	.62	62	16.3	4.5	8.7	4200	6,900	1140	.93	8.0	9,100	3.1	29	2180	3,030	680	930	480	910	860
Oak, Spanish (lowland)...........	....do....	3	7	63	78	.61	.71	67	16.4	5.2	10.8	6500	10,800	1790	1.32	14.7	12,300	3.8	54	3760	4,620	940	1320	800	1270	1240
Oak, water.......	....do....	5	10	61	81	.56	.68	63	16.4	4.2	9.3	5600	8,900	1550	1.14	11.1	11,600	3.8	39	3200	3,740	770	1240	820	1050	1010

TABLE 1.- RESULTS OF TESTS ON 85 SPECIES OF WOOD TESTED IN A GREEN CONDITION IN THE FORM OF SMALL CLEAR PIECES—*Continued*

Common Name.	Locality Where Grown.	Number of Trees Tested.	Number of Rings per Inch.	Summerwood (Per Cent).	Moisture Content (Per Cent).	Specific Gravity, Oven Dry, Based on—		Weight per Cubic Foot (Green) (Pounds).	Shrinkage from Green to Oven-dry Condition			Static Bending.					Impact Bending.			Compression Parallel to Grain.		Compression Perpendicular to Grain—Fiber Stress at Elastic Limit (Pounds per Square Inch).	Shearing Strength Parallel to Grain (Pounds per Square Inch).	Tension Perpendicular to Grain (Pounds per Square Inch).	Hardness, Load Required to Imbed a 0.444-Inch Ball to One-half Its Diameter	
						Volume When Green.	Volume When Oven-dry.		In Volume (Per Cent of Dimensions When Green).	Radial (Per Cent of Dimensions When Green).	Tangential (Per Cent of Dimensions When Green).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Modulus of Rupture (Pounds per Square Inch).	Modulus of Elasticity (1000 Pounds per Square Inch).	Work in Bending—To Elastic Limit (Inch-pounds per Cubic Inch).	Work in Bending—To Maximum Load (Inch-pounds per Cubic Inch).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Work in Bending to Elastic Limit (Inch-pounds per Cubic Inch).	Height of Drop Causing Complete Failure, 50-pound Hammer (Inches).	Fiber Stress at Elastic Limit (Pounds per Square Inch).	Maximum Crushing Strength (Pounds per Square Inch).				End (Pounds).	Side (Pounds).
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
HARDWOODS—Con.																										
Oak, white........	Ark., La., Ind.	20	17	60	68	.60	.71	62	15.8	5.3	9.0	4700	8,300	1250	1.08	11.5	10,700	4.2	42	2990	3,560	830	1250	770	1120	1060
Oak, yellow........	Ark., Wis.	8	15	71	78	.56	.67	63	14.2	4.5	9.7	4600	8,200	1180	1.20	12.3	10,800	4.4	40	2870	3,460	870	1180	830	1000	1060
Poplar, yellow....	Tenn.	5	14	...	64	.37	.42	38	11.4	4.1	6.9	3200	5,600	1210	.48	5.6	8,000	2.6	17	2000	2,550	310	790	460	420	340
Sycamore	Ind., Tenn.	10	16	77	83	.46	.54	52	14.2	5.1	7.6	3300	6,500	1060	.60	7.5	8,800	3.3	26	2390	2,920	450	1000	630	700	610
Walnut, black.....	Ky.	5	12	...	81	.51	.56	58	11.3	5.2	7.1	5400	9,500	1420	1.16	14.6	11,900	4.5	37	3600	4,300	600	1220	570	960	900
Willow, black.....	Wis., Mo.	10	5	...	138	.34	.41	50	13.8	2.6	7.8	1800	3,800	560	.36	10.8	5,100	2.0	36	970	1,510	210	620	430	350	360
CONIFERS																										
Cedar, incense....	Cal., Ore.	8	16	30	108	.35	.36	45	7.6	3.3	5.7	3900	6,200	840	.94	6.4	7,300	2.4	17	2870	3,150	460	830	280	570	390
Cedar, Port Orford.	Ore.	5	24	25	52	.41	.47	39	10.7	5.2	8.1	3900	6,800	1500	.59	7.8	9,300	2.7	25	2970	3,280	380	880	240	560	480
Cedar, western red.	Wash., Mont.	10	20	36	39	.31	.34	27	8.1	2.5	5.1	3300	5,200	950	.64	5.0	7,100	2.4	17	2500	2,840	310	720	210	430	260
Cedar, white......	Wis.	5	23	36	55	.29	.32	28	7.0	2.1	4.9	2600	4,200	640	.60	5.7	5,300	2.0	15	1420	1,990	290	620	240	320	230

Cypress, bald.....	La., Mo.	10	16	31	87	.41	.47	48	10.7	3.8	6.0	4000	6,800	1190	.86	6.4	8,000	2.6	24	3100	3,490	470	820	280	470	380
Cypress, yellow...	Ore.	5	31	...	40	.40	.44	35	7.9	1.9	5.0	3600	6,200	960	.77	9.5	8,600	3.2	27	2390	2,880	410	820	260	520	410
Douglas fir.......	Wash., Ore.	18	13	35	36	.45	.52	38	12.6	5.0	7.9	5000	7,800	1580	.86	6.7	9,400	2.9	25	3400	3,940	530	910	200	510	470
Douglas fir.......	Mont., Wy.	10	22	27	38	.40	.44	34	10.6	3.6	6.2	3600	6,400	1180	.65	6.8	9,100	3.0	20	2520	3,000	450	880	350	450	400
Fir, Alpine........	Col.	5	15	14	47	.31	.32	28	9.0	2.5	7.1	2400	4,400	860	.39	4.4	5,300	1.6	9	1660	2,060	310	610	....	280	220
Fir, amabilis......	Ore., Wash.	20	8	26	102	.37	.42	47	14.1	4.5	10.0	3900	6,300	1300	.60	6.0	7,800	2.2	21	2380	2,930	320	670	240	360	310
Fir, balsam	Wis.	5	12	26	117	.34	.41	45	10.8	2.8	6.6	3000	4,900	960	.52	4.7	6,900	2.3	16	2220	2,400	210	610	180	290	290
Fir, grand........	Mont., Ore.	10	18	30	94	.37	.42	44	10.6	3.2	7.2	3600	6,100	1300	.58	5.6	8,100	2.6	22	2680	3,010	340	760	230	420	360
Fir, noble........	Ore.	5	23	17	41	.35	.41	31	13.6	4.9	9.1	3400	5,700	1280	.53	6.2	7,900	2.6	20	2370	2,700	310	700	180	300	250
Fir, white......	Cal.	5	10	30	156	.35	.39	56	10.2	3.4	7.0	3900	6,000	1130	.77	5.2	7,200	2.2	18	2610	2,800	440	730	260	380	330
Hemlock black....	Mont.	5	23	45	70	.42	.48	45	10.8	4.4	7.1	3500	6,000	940	.78	9.4	8,800	3.6	36	2590	2,890	400	880	360	580	460
Hemlock (eastern).	Tenn., Wis.	10	20	34	105	.38	.44	48	10.4	3.0	6.4	4200	6,700	1120	.88	6.8	7,900	2.8	20	2710	3,270	500	880	260	510	410
Hemlock (western).	Wash.	5	10	27	71	.38	.43	41	11.6	4.5	7.9	3400	6,100	1190	.58	6.0	7,800	2.4	20	2290	2,890	350	810	260	540	430
Larch, western....	Mont., Wash.	13	32	37	58	.48	.59	48	13.2	4.2	8.1	4600	7,500	1350	1.01	7.1	9,400	3.7	24	3250	3,800	560	920	230	470	450
Pine, Cuban.....	Fla.	5	17	44	47	.58	.68	53	12.7	5.9	7.5	5600	8,800	1630	1.10	7.9	11,300	3.9	37	3950	4,470	590	1030	290	570	630
Pine, jack........	Wis.	5	7	30	105	.39	.46	50	10.4	3.4	6.5	3000	5,400	920	.55	5.9	7,800	3.3	30	2250	2,580	380	760	310	380	370
Pine, Jeffrey......	Cal.	5	18	23	101	.37	.42	47	9.9	4.4	6.7	3200	5,000	980	.60	4.7	7,200	2.6	21	2030	2,370	350	690	260	320	340
Pine, loblolly.....	Fla., N. C., S. C.	15	8	42	70	.50	.59	54	12.6	5.5	7.5	4400	7,500	1380	.81	8.0	9,500	3.1	32	2870	3,580	550	900	280	400	450
Pine, lodgepole....	Col., Mont., Wy.	28	24	22	65	.38	.44	39	11.5	4.5	6.7	3000	5,500	1080	.49	5.6	7,200	2.3	20	2100	2,610	310	690	220	320	330
Pine, longleaf.....	Fla., La., Miss.	34	18	39	47	.55	.64	50	12.3	5.3	7.5	5400	8,700	1630	1.00	8.0	10,800	3.5	34	3840	4,390	600	1070	290	550	590
Pine, Norway.....	Wis.	5	22	41	54	.44	.51	42	11.5	4.6	7.2	3700	6,400	1380	.59	5.8	7,500	2.2	28	2470	3,080	360	780	190	360	340
Pine, pitch........	Tenn.	5	12	30	85	.47	.54	54	11.7	4.8	7.4	3700	6,700	1120	.75	8.5	9,100	3.4	29	2100	3,640	510	950	350	460	480
Pine, pond........	Fla.	5	13	35	56	.50	.58	49	11.2	5.1	7.1	4500	7,400	1280	.93	7.5	9,400	3.2	33	2990	3,660	540	940	280	460	510
Pine, shortleaf....	Ark., La.	12	12	40	64	.50	.58	50	12.6	5.1	8.2	4500	8,000	1450	.79	8.7	11,200	4.0	39	3650	3,810	480	890	330	490	560
Pine, sugar.......	Cal.	5	12	34	123	.36	.39	50	8.4	2.9	5.6	3300	5,300	970	.66	5.0	6,700	2.3	17	2340	2,600	350	710	270	330	320
Pine, table-mountain............	Tenn.	5	15	29	75	.49	.55	54	10.9	3.4	6.8	4500	7,500	1270	.94	8.1	10,200	3.8	29	2980	3,540	560	960	320	480	490
Pine, western white	Mont.	5	28	33	58	.39	.45	39	11.5	4.1	7.4	3500	5,700	1330	.54	5.1	7,600	2.3	23	2770	3,070	300	710	250	330	330
Pine, western yellow	Col., Mont., Ariz., Wash., Cal.	25	20	22	95	.38	.42	46	10.0	3.9	6.4	3100	5,200	1010	.54	5.1	6,700	2.3	19	2080	2,460	340	680	280	310	320
Pine, white.......	Wis.	5	16	31	74	.36	.39	39	7.8	2.2	5.9	3400	5,300	1070	.62	5.9	6,500	2.1	18	2370	2,720	310	640	260	300	300
Spruce, Engelmann	Col.	10	14	14	100	.31	.35	38	10.4	3.4	6.6	2500	4,200	830	.43	4.9	5,800	1.9	14	1740	1,980	290	590	....	250	240
Spruce, red.......	N. H., Tenn.	9	17	27	43	.38	.41	34	11.8	3.8	7.8	3400	5,700	1180	.56	6.1	7,200	2.3	18	2360	2,740	350	770	220	420	350
Spruce, Sitka.....	Wash.	5	9	24	53	.34	.37	33	11.2	4.5	7.4	3000	5,500	1180	.44	6.4	7,900	2.5	29	2280	2,600	330	780	230	430	370
Spruce, white.....	N. H., Wis.	7	14	27	46	.36	.43	33	14.8	3.7	7.3	3300	5,400	980	.66	5.7	6,800	2.0	20	2280	2,380	270	670	200	300	280
Tamarack.........	Wis.	5	20	38	52	.49	.56	47	13.6	3.7	7.4	4200	7,200	1240	.84	7.2	7,800	2.7	28	3010	3,480	480	860	260	400	380
Yew, Pacific......	Wash.	5	27	...	44	.60	.67	54	9.7	4.0	5.4	6500	10,100	990	2.46	20.2	13,100	6.2	38	3400	4,600	1040	1620	450	1340	1150

TABLE 2.—AVERAGE STRENGTH VALUES FOR COMPRESSION PARALLEL TO GRAIN, COMPRESSION PERPENDICULAR TO GRAIN, AND SHEARING TESTS ON AIR-SEASONED MATERIAL OF DIFFERENT SIZES

(*Bull.* 108, Forest Service.)

Species.	Compression parallel to grain.						Compression perpendicular to grain.					Shear.		
	Size of specimen.	Number of tests.	Moisture.	Crushing strength at elastic limit per square inch.	Modulus of elasticity per square inch.	Crushing strength at maximum load per sq. in.	Stress area.	Height.	Number of tests.	Moisture.	Crushing strength at elastic limit per square inch.	Number of tests.	Moisture.	Shearing strength per square inch.
	In.		P. ct.	Lb.	1000 lb.	Lb.	In.	In.		P. ct.	Lb.		P. ct.	Lb.
Longleaf pine...	4 ×5	46	26.3	3480	.....	4800	4 ×5	4	22	25.1	572	52	20.2	984
Douglas fir.....	6 ×6	259	20.3	3271	1038	4258	4 ×8	16	44	20.8	732	465	22.1	822
	2 ×2	247	18.7	3842	1084	5002	4 ×8	10	32	18.1	584			
							4 ×4	8	51	20.2	638			
							4 ×4	6	49	24.0	613			
							4 ×4	4	29	24.8	603			
Shortleaf pine...	6 ×6	29	15.7	4070	1951	6030	8 ×5	16	4	17.8	725	85	...	1135
	2 ×2	57	14.2	...	.....	6380	8 ×5	14	3	16.3	757			
							8 ×5	12	5	15.1	730			
							5 ×5	8	6	15.0	918			
							2 ×2	2	57	13.9	926			
Western larch...	6 ×6	112	16.0	...	.....	5145	8 ×6	16	17	18.8	491	193	15.0	905
	4 ×4	81	14.7	...	.....	6161	8 ×6	12	18	17.6	526			
	2 ×2	270	14.8	...	.....	5934	5 ×4	8	22	13.3	735			
Loblolly pine ...	6 ×6	23	...	3357	1693	5005	8 ×5	16	12	19.8	602	156	11.3	1115
	5 ×5	10	22.4	2217	545	2950	8 ×5	8	7	22.9	679			
	4 ×8	8	19.4	3010	633	3920	4 ×5	8	8	19.5	715			
	2 ×2	69	...	...	.....	5547								
Tamarack......	6 ×7	3	15.7	2257	1042	3323	2 ×2	2	57	16.2	697	60	14.0	897
	4 ×7	3	13.6	3780	1301	4823								
	4 ×4	57	14.9	3386	1353	4346								
	2 ×2	66	14.6	...	.....	4790								
Western hemlock	6 ×6	102	18.6	4840	2140	5814	7 ×6	15	25	18.2	514	131	17.7	924
	2 ×2	463	17.0	4560	1923	5403	6 ×6	6	26	16.8	431			
							4 ×4	4	6	15.9	488			
Redwood.......	6 ×6	18	16.9	...	.....	4276	8 ×6	16	5	25.4	548	95	12.4	671
	2 ×2	115	14.6	...	.....	5119	6 ×6	12	6	14.7	610			
							7 ×6	9	5	14.8	500			
							3 ×6	14	2	12.6	470			
							2 ×6	12	2	16.2	498			
							2 ×6	10	4	14.3	511			
							2 ×6	8	2	13.2	429			
							2 ×2	2	145	13.8	564			
Norway pine. ..	6 ×7	4	15.2	2670	1182	4212	2 ×2	2	36	10.0	924	44	11.9	1145
	4 ×7	2	22.2	3275	1724	4575								
	4 ×4	55	16.6	3048	1367	4217								
	2 ×2	34	11.2	...	.....	7550								

TABLE 3.—RATIOS OF AVERAGE STRENGTH VALUES FOR AIR-SEASONED MATERIAL TO THOSE FOR GREEN MATERIAL.* (*Bull.* 108, Forest Service)

Species.	Bending.				Compression parallel to grain.			Compression perpendicular to grain.	Shear.
	Fiber stress at elastic limit per square inch.	Modulus of rupture per square inch.	Modulus of elasticity per square inch.	Horizontal shear per square inch.	Crushing strength at elastic limit per square inch.	Crushing strength at maximum load per square inch.	Modulus of elasticity per square inch.	Crushing strength at elastic limit per square inch.	Shear strength per square inch.
	Lb.	Lb.	1000 Lb.	Lb.	Lb.	Lb.	1000 Lb.	Lb.	Lb.
Longleaf pine:									
Structural sizes. . . .	0.99	0.94	1.16	0.77	1.00	1.00	. . . . . .	1.01	
Small specimens. . . .	1.36	1.27	1.13	. . . .	. . . . . .	.	. . . . . .	. . . . . .	1.01
Douglas fir:									
Structural sizes. . . .	1.15	1.06	1.02	1.33	1.18	1.22	.73	1.12	
Small specimens. . . .	1.28	1.25	1.06	. . . .	1.10	1.24	.56	. . . . . .	1.08
Shortleaf pine:									
Structural sizes. . . .	1.44	1.19	1.17	1.10	1.66	1.76	1.26	2.26	
Small specimens. . . .	1.79	1.57	1.28	. . . .	. . . . . .	1.79	. . . . . .	2.32	1.61
Western larch:									
Structural sizes. . . .	1.05	1.18	1.14	1.18	. . . . . .	1.64	. . . . . .	1.31	
Small specimens. . . .	1.38	1.42	1.19	. . . .	. . . . . .	1.60	. . . . . .	. . . . . .	1.29
Loblolly pine:									
Structural sizes. . . .	1.16	1.19	1.07	1.30	1.47	1.46	2.20	1.31	
Small specimens. . . .	1.26	1.19	1.02	. . . .	. . . . . .	1.71	. . . . . .	. . . . . .	1.77
Tamarack:									
Structural sizes. . . .	1.33	1.21	1.10	1.15	1.40	1.34	.98		
Small specimens. . . .	2.33	2.26	1.09	. . . .	. . . . . .	1.60	. . . . . .	. . . . . .	1.32
Western hemlock:									
Structural sizes. . . .	1.25	1.21	1.20	1.07	1.67	1.73	1.32	1.09	
Small specimens. . . .	1.44	1.42	1.17	. . . .	1.55	1.59	1.11	. . . . . .	1.47
Redwood:									
Structural sizes. . . .	.92	.87	.85	. . . .	. . . . . .	1.16	. . . . . .	1.21	
Small specimens. . . .	1.00	1.12	1.08	. . . .	. . . . . .	1.29	. . . . . .	.99	.90
Norway pine:									
Structural sizes. . . .	1.63	1.57	1.25	1.20	1.48	1.66	1.36		
Small specimens. . . .	1.88	1.64	1.21	. . . .	. . . . . .	3.01	. . . . . .	. . . . . .	1.94

* Ratios were based on the unit values indicated in column headings of Table 3.

of the varieties of hickory and oak and reaching 55 per cent for Pacific post oak.

With the exception of the longleaf pine specimens, which judging from their moisture content must have been pretty green, the air-seasoned structural timbers of every species were stronger in compression than the green timbers (see Art. 241).

228. Tensile Strength of Wood.—When a properly shaped wooden stick is subjected to tensile forces acting parallel to the grain it is found to have greater strength than can be developed under any other kind of stress. Indeed, the tensile strength of wood parallel to the grain is so great that much difficulty is encountered in designing end connections so that the tensile strength of a piece can be developed. Therefore, wood tension members are rarely used. Moreover, since the tensile strength parallel to the grain is two to four times the compressive strength, the latter governs the strength of beams. Therefore the tensile strength with the grain is rarely tested.

The tensile strength parallel to the grain is influenced to some extent by the nature of the wood elements and their arrangement, but principally by the straightness of the grain and the thickness of the walls of the longitudinal elements. When failure occurs these elements are ruptured transversely. Knots greatly reduce the tensile strength parallel to the grain and are a great menace to strength when present in timbers subjected to such stresses (see Art. 240). The tensile strength appears to be less affected by moisture than are other mechanical properties.

Across the grain, the tensile strength of wood is small. It is a property closely related to cleavability, and it often determines the strength of a beam which has cross-grain or spiral-grain in the tension fibers. Failure in tension across the grain occurs through separation of the cells and fibers in longitudinal planes. Knots, shakes, and checks all reduce the tensile strength of wood across the grain. The form of specimen used by the Forest Products Laboratory in making the test is shown in Fig. 1.

Data in *Circular No. 213* of U. S. Forest Service show that the tensile strength of wood across a radial plane is less than the tensile strength across a plane tangent to the rings. This difference is especially pronounced in the oaks and other hardwoods having large medullary rays. It is probable, therefore, that these rays considerably weaken the tensile strength of wood across a radial plane.

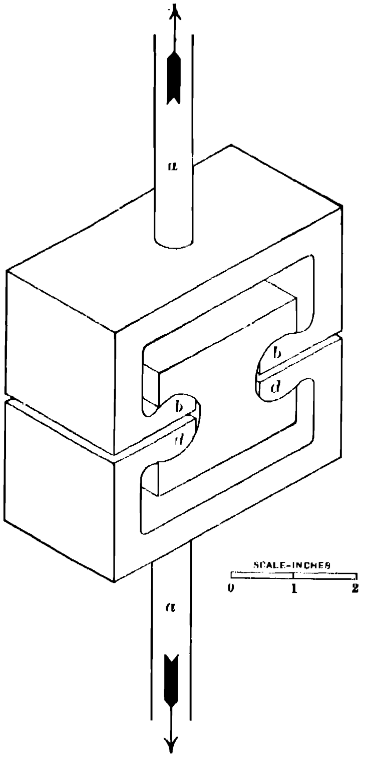

Fig. 1.—Type of Test Used by Forest Products Laboratory to Find Tensile Strength of Wood Across Grain. (Betts and Greeley before Int. Engr. Congress, 1915.)

For the conifers, from which most structural timbers are secured, the cross-grained tensile strength of small perfect specimens of green wood runs between 180 and 450 lb. per square inch, while for the oaks it varies between 500 and 1000 lb. per square inch. The smallness of these values must be remembered in computing the safe strengths of beams having cross-grain in the tension fibers.

229. The Shearing Strength of Wood.—Although shearing stresses are often of small moment in metal beams and other structural elements, they are frequently of very great importance in members made of wood. Thus the horizontal shear stress at the neutral axis of a short, deep wooden beam may be sufficiently great to produce a failure like that of Fig. 2. If the mortise-and-tenon joint, shown in Fig. 3, is loaded so that the tenon presses downward upon the mortise, transverse shear stresses are produced on the tenon; and shear stresses parallel to the grain are caused in the vertical piece on planes *AC* and *BD*. In most cases failure in the tenon is due to bending rather than shear, but the pushing out of the piece *ABCD* is an example of shear failure.

(Courtesy Forest Products Laboratory.)

FIG. 2.—Failure of a Large Wooden Stringer by Horizontal Shear.

If the shearing stresses act on planes tangent to the growth rings, the resistance of the various woods is quite small, ranging from about 600 to 1000 lb. per square inch for small green specimens of the structural conifers and from 1000 to 1500 lb. per square inch for similar pieces of oak, hickory, elm, maple, sycamore, beech, birch, and white ash (see Table 1). *Circular 213* of U. S. F. S. shows that there is little difference between the strengths of small pieces of green coniferous wood subjected to shearing parallel to the rings (tangential shear), and the strengths of like pieces subjected to shearing stresses acting on vertical radial planes (radial shear). Among the hardwoods the resistance to radial shear appears to be slightly the greater. In Fig. 4 are shown failures of pieces of green longleaf pine in radial shear (22) and in tangential shear (30).

Turning our attention to the results in Table 4 we find the calculated horizontal shear stresses developed in tests of beams of structural sizes. These shear stresses were computed from the formula $S_h = \frac{3}{2}\frac{V}{a}$; where S_h = horizontal shear stress, V = maximum vertical shear and a = area of rectangular cross-section of beam. Comparing these results with the values for like woods found in Table 1, we observe that the computed stresses for the large beams are much lower than the shearing strengths of small specimens. This discrepancy is due principally to defects, shakes, and checks which cut down the area under shear. Since the formula assumes a full cross-section, the results given by it will be smaller than the stresses in the net sections of wood. The lesson taught is to use values from the tests on large beams failing in shear as a basis for design. Both Table 3 and 4 show that air-seasoned coniferous timber is, in most cases, stronger than green timber. Longleaf pine and redwood are, however, exceptions to this rule.

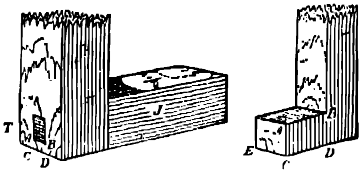

FIG. 3.—Wood Members Subjected to Longitudinal Shear.

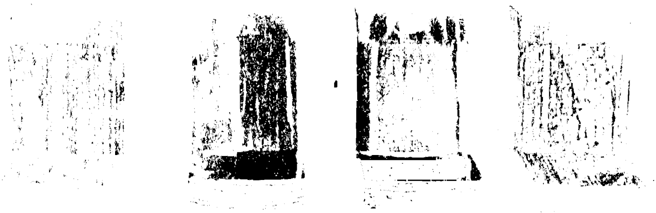

FIG. 4.—Shear Failures Parallel to Grain in Green Longleaf Pine. Nos. 32_1 and 22_1 plane of shear radial, Nos. 32 and 30 plane of shear tangential to annual rings. (*Bulletin No.* 70, Forest Service.)

230. The Strength of Wood in Cross-bending.—Because of the great use of wood for beams, stringers, joists, rafters and other parts which are subject to bending, the cross-bending test is of much value in determining the quality of wood. By it one can measure the strength, toughness, and stiffness of the timber. Furthermore, the cross-bending test exposes weaknesses caused by defects better than does any other test. Unless very large testing machines are at hand, it is the only test which can be used to find the strength of timbers of structural sizes.

It will be remembered from Mechanics of Materials that the modulus of rupture in cross-bending is a fictitious measure of the ultimate unit

TABLE 4.—CALCULATED SHEARING STRESSES DEVELOPED IN STRUCTURAL BEAMS

(From *Bull.* 108, Forest Service)

Species.	Total Number of Tests.		First Failure by Shear.				Shear following other Failure.				No Shear Failure.			
			Green.		Dry.		Green.		Dry.		Green.		Dry.	
	Green.	Dry.	Per cent of total.	Average calculated shear per square inch.	Per cent of total.	Average calculated shear per square inch.	Per cent of total.	Average calculated shear per square inch.	Per cent of total.	Average calculated shear per square inch.	Per cent of total.	Average calculated shear per square inch.	Per cent of total.	Average calculated shear per square inch.
				Lb.		Lb.		Lb.		Lb.		Lb.		Lb.
Longleaf pine. .	17	9	54	353	56	272	23	374	0	. . .	23	218	44	286
Douglas fir. . . .	191	91	2	166	6	221	22	205	49	294	76	264	45	247
Shortleaf pine. .	48	13	17	332	46	364	6	327	[illegible]	418	77	276	46	340
Western larch. .	62	52	8	288	27	340	16	314	21	370	76	268	52	287
Loblolly pine. .	111	25	7	335	28	434	2	356	16	546	91	237	56	255
Tamarack.	30	9	10	261	33	299	3	263	0	. . . .	87	228	67	283
Western hemlock.	39	44	5	288	23	307	28	281	68	438	67	250	9	417
Redwood.	28	12	7	302	0	. . . . . .	11	218	17	250	82	283	83	227
Norway pine. . .	49	10	6	232	10	278	6	266	0	. . .	88	209	90	304

stress on the extreme fiber at the danger section. The modulus of rupture is computed from the formula $S_m = \frac{M_m c}{I}$; where the modulus, S_m = unit stress on extreme fiber, M_m = maximum bending moment, c = distance from neutral axis to extreme fiber, and I = moment of inertia of the cross-section about the neutral axis. It will be recalled that the modulus of rupture as determined by this formula is intermediate between the tensile and compressive strengths and that it does not, therefore, truly represent the unit stress on the extreme fiber. The discrepancy between the calculated unit stress and the actual unit stress is due to the non-linear relation of stress to deformation when the elastic limit is exceeded, and also to the shifting of the neutral axis. The movement of the latter is brought about by the difference in the stress-deformation relations in tension and compression. Although a fictitious stress, the modulus of rupture is, nevertheless, a valuable index of quality of the wood. Also, if the elastic limit of the beam is determined, the ratio of the modulus of rupture [illegible] the unit stress on the extreme fiber at the elastic limit serves as a measure of the capacity of the beam to resist a momentary overload. Beams in which there is a well-marked difference between these stresses are preferable, since such members give ample warning of approaching failure.

The initial failure of long beams of uniform wood is indicated by a wrinkling of the overstressed compression fibers, much like the failure which occurs in compression prisms. Final failure of such beams is generally in tension. It is accompanied by more or less snapping as the individual fibers begin to break, and a load report when the maximum load is reached. Very dry specimens sometimes fail very suddenly in tension before any wrinkling of the compression fibers is noticeable. On the other hand, green test-pieces fail silently in compression without rupturing of the tensile fibers. Frequently, short deep beams fail by horizontal shear This type of failure is sudden and is more common in well-seasoned timbers of structural sizes than in green timbers or in small beams. Very often shear failures result from defects.

Long, narrow beams must be restrained laterally and supported in such manner that the wide sides are vertical. If the first condition is not fulfilled, the member will fail from column action in the compression fibers. Unless the second condition is met the strength of the beam may be very seriously reduced through the inclination of the neutral axis. In laying joists for flooring these requirements are satisfied by diagonal bracing which the carpenter calls " bridging."

The relative strengths of the woods from various species of trees can be obtained from the values of the fiber stress at elastic limit and modulus of rupture which are tabulated in Table 1. It will be noted that the hardwoods as a class considerably exceed the conifers in static bending strength. Black and honey locust, the hickories, lowland Spanish oak, cork elm, blue gum, and white oak are the stronger varieties of the hardwoods. Among the soft woods longleaf, Cuban and shortleaf pines, yew, Douglas fir, and tamarack are the strongest.* Longleaf pine averages about the same in static bending strength as maple and red oak of the hardwoods. The ratios of the modulus of rupture to fiber stress at elastic limit range from 2.2 to 1.5 for the hardwoods and from 1.8 to 1.5 for the conifers. These ratios will be lower in beams of structural sizes because of defects.

In Table 5 strength values for cross-bending tests on air-seasoned timbers of structural size may be found. These results show very conclusively that the transverse strengths of small timbers are proportionately much higher than the strengths of large timbers. These discrepancies, which for the tests cited amount to 50 per cent in a number of instances, are largely due to the greater uniformity of the small test-pieces and their freedom from defects. Selected structural timbers in green state are, in general, about three-fourths as strong as small, clear pieces taken from them.

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* Bamboo is a very strong wood in cross-bending, as the results of 8 tests by J. B. Johnson show. He used pieces which varied in diameter (between joints) from 0.54 in. to 1.25 in., and in thickness from 0.08 in. to 0.17 in. The spans varied from about 28 in. for the larger pieces to 8 in. for the smaller. Values of the modulus of elasticity ranged from 1,960,000 to 3,020,000 and averaged 2,380,000 lb. per square inch. The moduli of rupture varied from 19,600 to 41,100 and averaged 27,400 lb. per square inch. The average elastic limit was 17,300 lb. per square inch. All computations were based on the properties of the annular section. The average elastic resilience in inch-pounds per pound of weight of specimen was 216.

TABLE 5.—AVERAGE STRENGTH VALUES FOR AIR-SEASONED TIMBER BEAMS

(From Forest Service *Bull.* No. 108)

Species.	Sizes		Number of tests.	Moisture.	Rings per inch.	Fiber stress at elastic Limit.		Modulus of rupture.		Modulus of elasticity.		Calculated shear.	
	Cross-section	Span.				Average per square inch.	Ratio to 2 by 2 inches.	Average per square inch.	Ratio to 2 by 2 inches.	Average per square inch.	Ratio to 2 by 2 inches.	Average per square inch.	Ratio to 2 by 2 inches.
	In	In.		P ct.		Lb		Lb.		1000 Lb.		Lb.	
Longleaf pine	8 × 16	180	5	22.2	16.0	3390	.50	4,274	0.37	1747	1.00	288	0.75
	6 × 16	132	1	23.4	17.1	3470	.51	6,610	.57	1501	.86	388	1.01
	6 × 10	177	2	19.0	8.8	4560	.68	7,880	.68	1722	.99	214	.56
	4 × 11	180	1	18.4	23.9	3078	.46	8,000	.69	1660	.95	251	.66
	6 × 8	177	6	20.0	13.7	4227	.63	8,196	.71	1634	.94	177	.46
	2 × 2	30	17	15.9	13.9	6750	1.00	11,520	1.00	1740	1.00	383	1.00
Douglas fir	8 × 16	180	91	20.8	13.1	4563	.68	6,372	.61	1541	.91	260	.64
	5 × 8	180	30	11.9	12.2	5065	.76	6,777	.65	1848	1.09	218	.52
	2 × 2	24	211	19.0	16.4	6686	1.00	10,378	1.00	1695	1.00	419	1.00
Shortleaf pine	8 × 16	180	3	17.0	12.3	4220	.54	6,030	.50	1517	.85	398	.98
	8 × 14	180	3	16.0	12.3	4253	.55	5,347	.44	1757	.98	307	.76
	8 × 12	180	7	16.0	12.1	5051	.65	7,331	.60	1803	1.01	361	.89
	5 × 8	180	6	12.2	22.5	7123	.92	9,373	.77	1985	1.11	301	.74
	2 × 2	30	67	14.2	13.7	7780	1.00	12,120	1.00	1792	1.00	404	1.00
Western larch	8 × 16	180	23	18.3	21.9	3343	.57	5,440	.53	1409	.90	349	.96
	8 × 12	180	29	17.8	23.4	3631	.62	6,186	.60	1549	.99	295	.81
	5 × 8	180	10	13.6	27.6	4730	.80	7,258	.71	1620	1.04	221	.61
	2 × 2	30	240	16.1	26.8	5880	1.00	10,254	1.00	1564	1.00	364	1.00
Loblolly pine	8 × 16	180	14	20.5	7.4	4195	.81	6,734	.72	1619	1.10	462	1.45
	6 × 16	126	4	20.2	5.0	2432	.47	4,295	.46	1324	.90	266	.84
	6 × 10	174	3	21.3	4.7	3100	.60	6,167	.66	1449	.99	173	.54
	4 × 12	171	4	19.8	4.7	2713	.52	5,745	.61	1249	.85	185	.58
	8 × 8	180	9	22.9	4.9	2003	.56	4,557	.48	1136	.77	93	.29
	6 × 7	141	2	21.1	5.0	2990	.58	4,968	.53	1286	.88	116	.36
	4 × 8	132	8	19.5	9.1	3384	.65	6,194	.66	1200	.82	196	.62
	2 × 2	30	123	17.6	6.6	5170	1.00	9,400	1.00	1467	1.00	318	1.00
Tamarack	6 × 12	162	5	23.0	15.1	3434	.45	5,640	.43	1330	.82	318	.75
	4 × 10	162	4	14.4	9.7	4100	.54	5,320	.41	1356	.84	252	.59
	2 × 2	30	47	11.3	16.2	7630	1.00	13,080	1.00	1620	1.00	425	1.00
Western hemlock	8 × 16	180	44	17.7	17.8	4398	.69	6,420	.62	1737	1.04	406	1.06
	2 × 2	28	311	17.9	19.4	6333	1.00	10,369	1.00	1666	1.00	382	1.00
Redwood	8 × 16	180	6	26.3	22.1	3797	.79	4,428	.57	1107	.96	204	1.05
	6 × 12	180	6	16.1	17.7	3175	.66	3,353	.43	728	.64	167	.60
	7 × 9	180	6	15.9	15.2	3280	.69	4,002	.51	1104	.96	147	.53
	3 × 14	180	6	13.1	24.4	...	...	5,033	.64	...	...	291	1.04
	2 × 12	180	5	13.8	11.4	3928	.82	5,336	.68	1249	1.09	260	.93
	2 × 10	180	5	13.8	24.8	3757	.79	4,606	.59	1198	1.05	186	.67
	2 × 8	180	6	13.7	20.7	4314	.90	5,050	.65	1313	1.15	166	.60
	2 × 2	28	122	15.2	18.8	4777	1.00	7,798	1.00	1146	1.00	279	1.00
Norway pine	6 × 12	162	5	16.7	8.1	2968	.56	5,204	.61	1123	.97	286	1.02
	4 × 10	162	5	13.7	12.0	5170	.98	6,904	.81	1712	1.48	317	1.13
	2 × 2	30	60	14.9	11.2	5280	1.00	8,470	1.00	1158	1.00	281	1.00

Results in Table 3 show that air-seasoning is somewhat beneficial to the strength of structural timbers. It is probable that a more complete drying would have made the strengths of the air-seasoned timbers still greater.

231. The Time Element in the Loading of Timber.—Since timber yields more rapidly under heavy loads than most materials of construction, it is quite necessary to standardize the rate of loading in order that test data may not be influenced by this factor. Extensive tests by the Forest Service led it to adopt the following rates of unit deformation per minute for the testing program of the Forest Products Laboratory.

Bending tests on timber of structural size	0.0007
Bending tests on small beams	0.0015
Compression parallel to grain, large prisms	0.0015
Compression parallel to grain, small prisms	0.0030
Shearing along the grain	0.0150

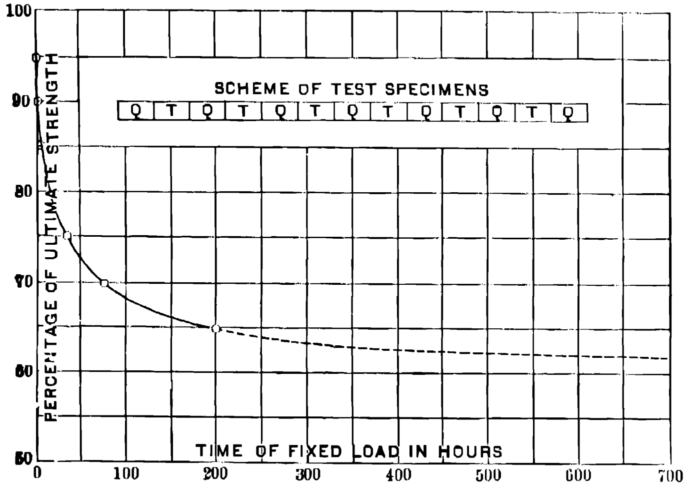

FIG. 5.—Results of Time Tests on Dry Longleaf Pine in Compression Endwise. The specimens marked Q were tested quickly, as in one or two minutes; those marked T were loaded with various percentages of the breaking load of the two adjacent specimens, and this load was left on until failure occurred, and the time noted.

For the bending tests these rates apply to the extreme fiber at the dangerous section. The speed of the movable head (n) of the testing machine in bending tests is given by $n=\frac{\epsilon l^2}{6h}$ for a center load, and $n=\frac{\epsilon l^2}{5.4h}$ for a third-point loading. In these equations ϵ = unit deformation per minute, l = the span and h = the depth of a rectangular beam. According to Tiemann * variations of 25 per cent in the above rates will not affect strength more than 2 per cent.

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* For a more complete discussion see *Proc. A. S. T. M.*, Vol. 8, p. 541.

In order that proper factors of safety may be established on a basis of testing machine results, it is very desirable that the strength of timber under dead loads be determined. Experimentation by the Forest Products Laboratory indicates that the modulus of rupture in beams under load for several years is approximately 56 per cent of the value obtained in an ordinary test lasting 4 or 5 minutes and that the modulus obtained for a quick loading lasting about half a minute is about 10 per cent greater than the values obtained at normal speeds. In Fig. 5 appear the results of approximately seventy-five end compression tests by J. B. Johnson on $1\frac{5}{8}\times1\frac{5}{8}\times3$-in. prisms. All specimens were cut from a single plank of longleaf pine which was ripped into prisms 40 in. long. The specimens were cut from each long prism as indicated in Fig. 5 and dressed to the above size. All tests were made in a 30,000-lb. universal machine. For dead-load tests the prisms were bedded on a nest of four vertical car springs which deformed about an inch under the imposed loads. By means of this elastic base the yielding of the specimen was taken up and load of almost constant intensity maintained throughout the test. Each plotted point in Fig. 5 represents three to six tests. These data indicate that the long-time compressive strength of wood parallel to the grain cannot be taken greater than two-thirds of the usual testing machine values.

Moore and Kommers report that the endurance limit in repeated bending tests of wood approximates one-fourth of the modulus of rupture determined at normal speeds.

STIFFNESS AND OTHER MECHANICAL PROPERTIES

232. The Stiffness of Wood.—Stiffness in a structure is often of as much importance as strength, but it is much more frequently neglected in designing. Floors must be sufficiently stiff so that they will not deflect appreciably under working loads or else they give one the feeling of insecurity. If a floor sustains a plastered ceiling its deflection under working load should not exceed $\frac{1}{360}$ of the span. Likewise the deflection of rafters should be limited, if it is desirable to avoid the disagreeable appearance of a sagged roof.

Stiffness in compression members is not often of moment in design. It is measured by the modulus of elasticity which is computed from the ratio of unit stress to unit strain. For beams the modulus of elasticity (E) may be computed from the equation $E=\frac{Pl^3}{\beta fI}$; where P = a certain load within the elastic limit of the beam, f = deflection corresponding to P, l = length of span, I = moment of inertia of cross-section about the neutral axis and β = a constant depending on the end conditions and the method of loading the beam. For a center load on a simple beam, $\beta=48$; for the case of a simple beam loaded with two equal concentrated loads (P, P) at the third points of the span, $\beta=\frac{648}{23}$.

In general, the denser woods are the stiffer, as may be seen by reference to Table 1. There is not, however, much difference between stiffness of the softwoods as a class and the stiffness of the hardwoods, nor are there as wide variations in the stiffnesses of the various species of wood as in the strengths. Values in Table 3 show that green timber is less stiff than air-seasoned; and, from results in Table 5, it appears that the structural sizes of timber are about as stiff as the small clear sticks.

Fig. 6 shows typical load-deflection and load-deformation curves for wood. These figures also indicate the method of finding the elastic limit and the correction of curve when it does not pass through the origin. Other load-deformation curves for wood may be seen in Fig. 13.

233. Toughness.—A wood which has a large capacity to resist shocks or blows is called tough. The spokes of an automobile or wagon, the tongue of a wagon and its axles, the handle of the axe or sledge all must be tough that they may absorb without injury the shocks which they receive. In order to be tough a wood must have both strength and flexibility.

Toughness is best measured by the energy of the blow required to rupture a beam in transverse impact. A less reliable index of toughness is obtainable from the energy of rupture in cross-bending. The latter test, however, is more easily made than the former and of more general value, since static strength and stiffness may also be gotten from it. The torsion test has also been used to measure the toughness of wagon spokes.

In Table 1 the average work done in deforming a large number of small wooden specimens in both static and impact bending tests has been recorded. The methods of determining the various results in static bending have been considered in Ch. I and III. In the impact tests the height of drop was increased by 1- or 2-in. intervals until failure took place. The height of drop at the elastic limit was gotten by plotting height of drop (h) against the square of the deflection (f) and determining the value h' at which the curve deviated from a straight line. The fiber stress at elastic limit (S_e) was calculated from $S_e=\frac{3Wh'l}{fbd^2}$; the modulus of elasticity (E) from $E=\frac{l^2\times S_e}{6hf}$; and the elastic resilience (K) from $K=\frac{Wh'}{lbd}$. The undefined symbols are W = weight of hammer, l = length of span, b = breadth of beam, and d = depth of beam.

From the test results on green timber, it will be observed that the total

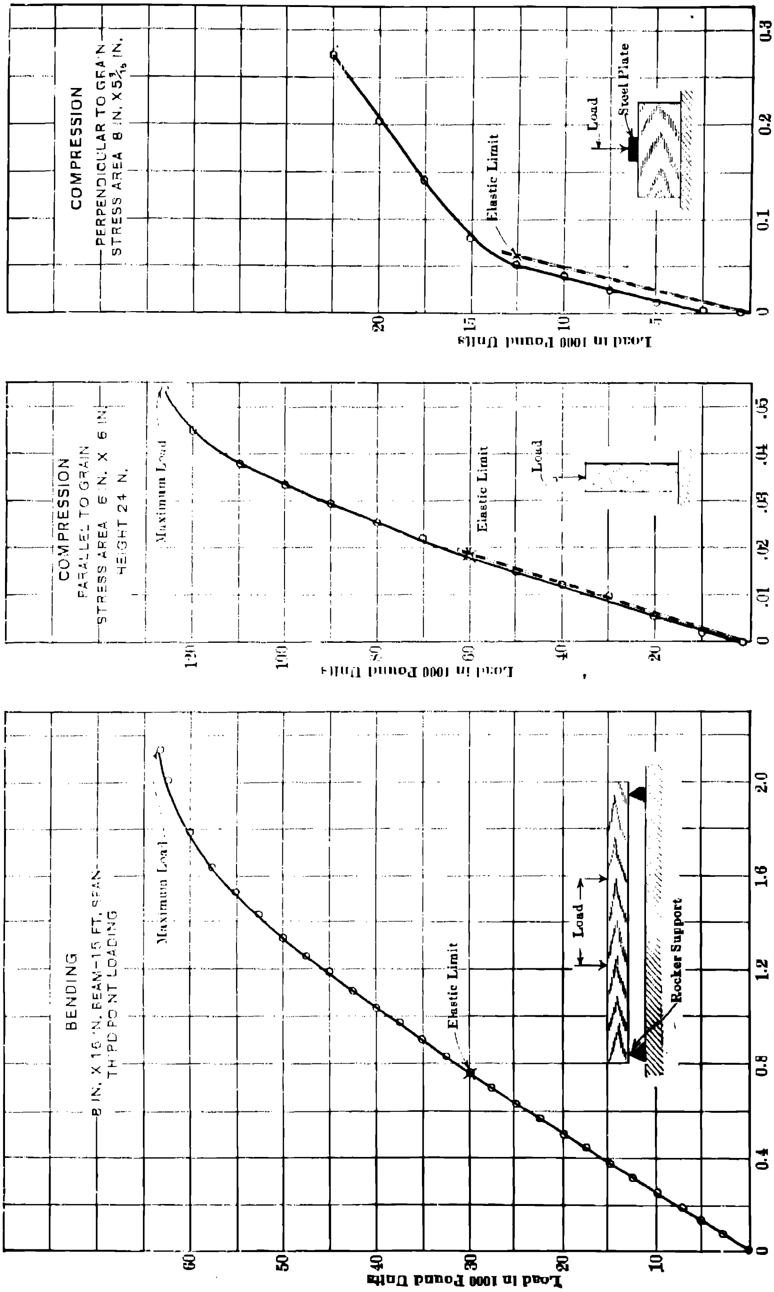
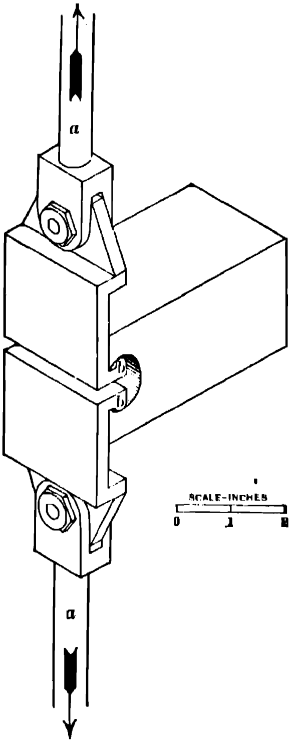


Fig. 6.—Representative Stress Deformation Diagrams for Bending, Compression Parallel to the Grain, and Compression Perpendicular to the Grain. (From *Bulletin No.* 108, Forest Service.)

work in static bending and the height of drop causing complete failure in impact bending vary with different species in approximately the same manner. With these calculated values as criteria, it is obvious that the hardwoods as a class excel the conifers in toughness. Among the hardwoods, osage orange, hickory, rock elm, slippery elm, honey locust and hackberry are very tough; while basswood and sycamore are more brittle than many of the softwoods. Longleaf pine is the only one of the conifers possessing much toughness.

Seasoning when unaccompanied by checking generally increases toughness, but in chestnut, gum and willow it causes a marked decrease in toughness and, to a less extent, adversely affects hickory. In general, greenwood is tougher than seasoned material.

234. Cleavability is the measure of the ease with which wood may be split. This property is of considerable moment in the working of wood, especially in splitting fence rails and firewood. Woods which must be fastened by nails and screws should have a high resistance to splitting.



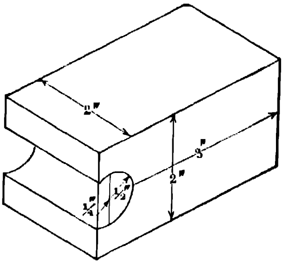


FIG. 7.—Type of Cleavability Test and Specimen Adopted by Forest Products Laboratory. (Betts and Greeley before Int. Engr. Congress, 1915.)

Since splitting is accomplished by wedging apart the longitudinal elements, it is closely related to tension, across the grain. At the Forest Products Laboratory, the test-piece of Fig. 7 is used to determine resistance to cleavage.

From data in *Circular 213*, it appears that most hardwoods split more easily along radial planes than along tangential surfaces. Among the conifers the difference in cleavage strength in the two directions is not great, but for longleaf pine and tamarack it is greatest across radial planes. Interlocking of the wood fibers causes high cleavage strength, while defects like shakes and checks reduce it. Knots may affect it either way, depending upon the number, position and character.

Honey locust, hickory, slippery elm, hard maple, and the oaks have the highest resistance to splitting. Basswood and the conifers split with comparative ease.

235. Hardness.—Both resistance to indentation and resistance to scratching are important properties in woods which are to be used for finishing and for furniture. These properties, together with the ability to wear without splintering determine the wearing resistance of wood for floors and pavements. Aside from the indentation tests no satisfactory type of test has been devised to measure these properties. However, experience shows that woods having marked difference in the character of the spring wood and summer wood (pine and oak), wear best when laid with the edge of the grain exposed to wear. With the fine-grained woods of uniform texture, like hard maple, the resistance to wear appears to be little affected by the method of sawing.

The resistance to indentation of a number of green woods is given in Table 1. Among the hardwoods, basswood, poplar, aspen, cottonwood, and willow are quite soft, whereas yew, a conifer, is remarkably hard. In green wood the hardness appears to be independent of the surface indented. Seasoning greatly increases resistance of all surfaces to indentation but affects the resistance of the end surfaces most.

CONDITIONS AFFECTING MECHANICAL PROPERTIES OF TIMBER

236. Density.—All the mechanical properties of clear wood are related to its density, which varies directly with the apparent specific gravity, ρ. Within a given species the relation is closer than between species. This is most pronounced in timbers of structural size where defects and moisture content considerably affect interspecies relationships.

From a large number of tests of small clear pieces made by the Forest Products Laboratory (see Bull. No. 676 and Technical Bull. No. 158, U. S. Dept. of Agric.) the following data were obtained:

Property.	Modulus of Rupture.	Modulus of Elasticity.	Work to Max. Load.	Compressive Strength		Shearing Strength (tangential).	Tension Across Grain.
				Parallel to Grain.	Normal to Grain.		
	lb./in.^{2}	1000 lb./in.^{2}	in lb./in.^{3}	lb./in.^{2}	lb./in.^{2}	lb./in.^{2}	lb./in.^{2}
Green.....	$17{,}600\rho^{1.25}$	2360ρ	$35.6\rho^{1.75}$	$6{,}730\rho$	$3000\rho^{2.25}$	$2750\rho^{1.33}$	$1950\rho^2$
Air-dry....	$25{,}700\rho^{1.25}$	2800ρ	$32.4\rho^{1.75}$	$12{,}200\rho$	$4630\rho^{2.25}$	$4000\rho^{1.33}$	$2100\rho^2$

It will be observed that the general law is $Q=C\rho^n$; where n is an exponent between 1.0 and 2.25, and ρ is computed from the volume of the wood at test and the oven dry weight.

Fig. 8 shows the relation between modulus of rupture and the specific gravity for 113 varieties of wood in air-dry and in green condition. In

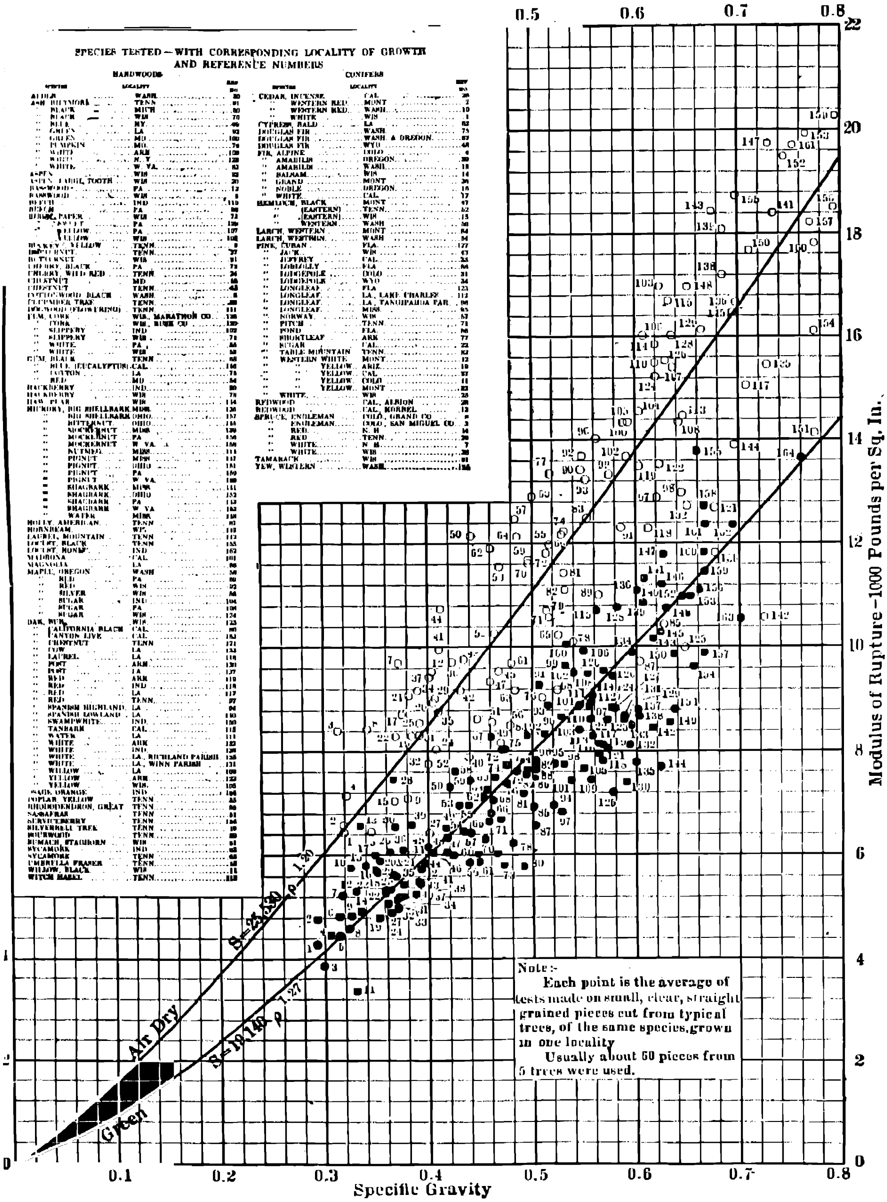


FIG. 8.—Relation between Bending Strength (s) and Specific Gravity (ρ) for 113 Woods. (Specific gravity is based on volume at test and dry weight. Diagram compiled at Forest Products Laboratory.)

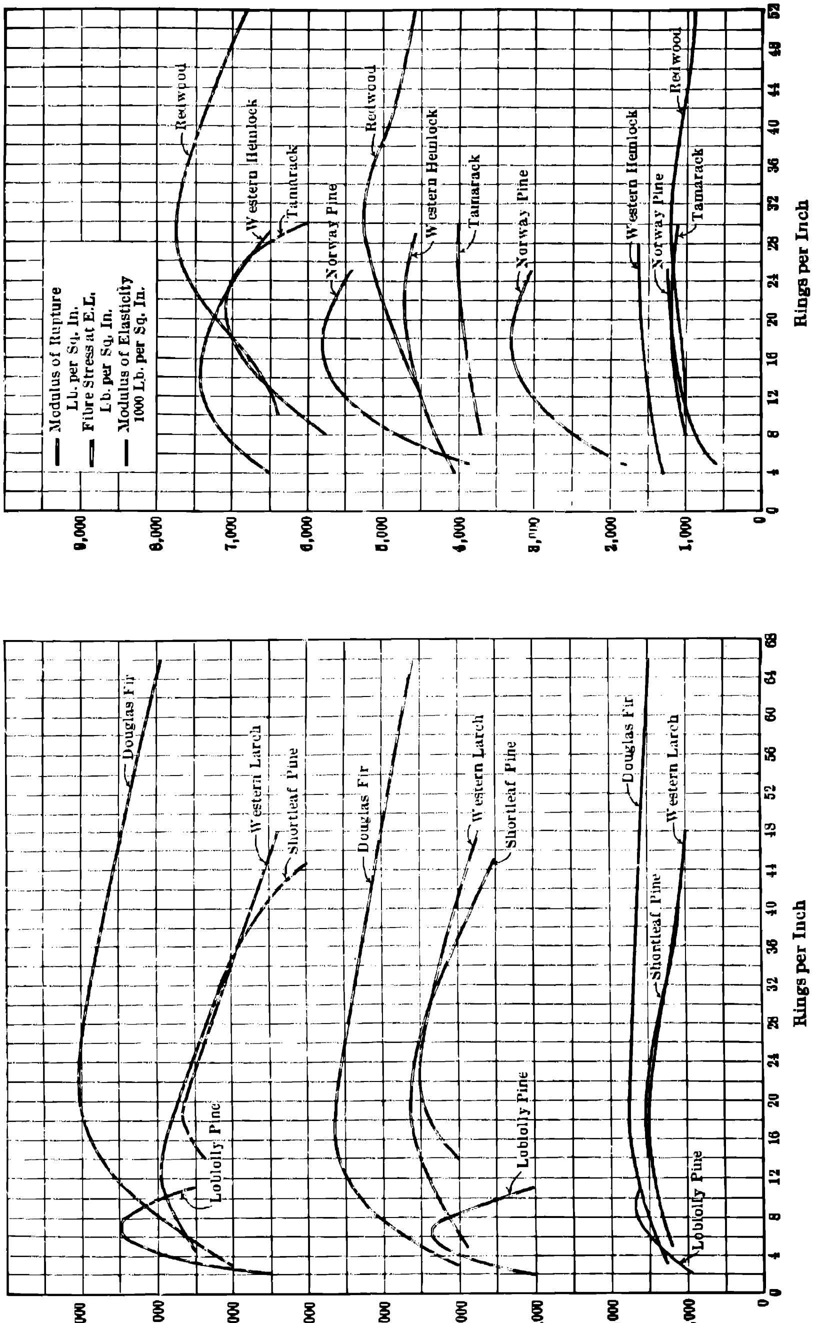


FIG. 9.—Relation of Modulus of Rupture, Fiber Stress at Elastic Limit, and Modulus of Elasticity to Rate of Growth, as Shown by Number of Rings per Inch. (From *Bull.* 108, Forest Service.)

standard specifications the value of specific gravity as a criterion of quality is evidenced by elimination of timbers of light weight from the select and dense select grades. Since specific gravity is affected by rate of growth, per cent summer wood, position of specimen in tree, and moisture content, the influence of these factors is next considered.

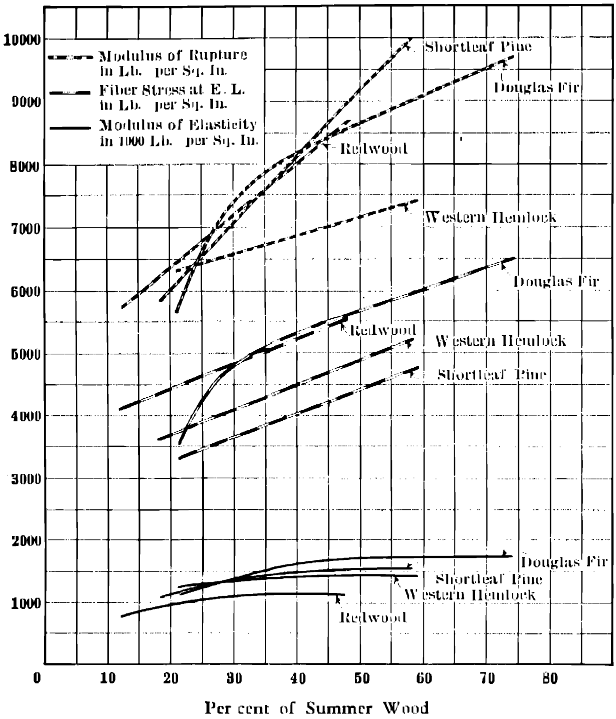


FIG. 10.—Relation of Modulus of Rupture, Fiber Stress at Elastic Limit, and Modulus of Elasticity to Percentage of Summer Wood. (From *Bull.* No. 108, Forest Service.)

237. Effect of Rate of Growth.—Fig. 9 illustrates the previously made statement that coniferous wood having a medium rate of growth is the strongest and stiffest. There is, however, a wide range in the most effective rates of growth for different conifers. In the dense hardwoods rapid growth is more desirable. In tests on green hickory the best strength was obtained from material having a rate of growth of 10 to 20 rings per inch, and the best toughness from specimens with less than 10 rings per inch (*Bull.* No. 80, Forest Service).

Whereas rate of growth is not so trustworthy a criterion of strength as the percentage of summer wood, the select grades of southern pine and Douglas fir are based on material containing not less than 6 nor more than 20 annual rings per linear inch.

238. Effect of Percentage of Summer Wood.—With most coniferous wood the summer wood is readily identified and forms a valuable index of the mechanical properties of the timber. The proportion of summer wood in a given coniferous timber is generally determined by estimating the ratio of the sum of the areas of the dark rings to the total cross-section.

Fig. 10 shows the relation of per cent summer wood to strength and stiffness for several coniferous woods. On account of the important relation which the per cent summer wood bears to mechanical properties a minimum percentage limit has been inserted in specifications for dense structural timber (see Art. 250).

239. Relations of Mechanical Properties to Position in Tree.—Since wood in the lower part of the trunk of a tree is more dense than that higher up, and since the densest wood at any given height is situated between the pith and the middle ring of the cross-section, a small variation in the strength of wood due to position in the tree will be found. Fig. 11 shows how the strength of wood in western larch trees varies with the height above ground.

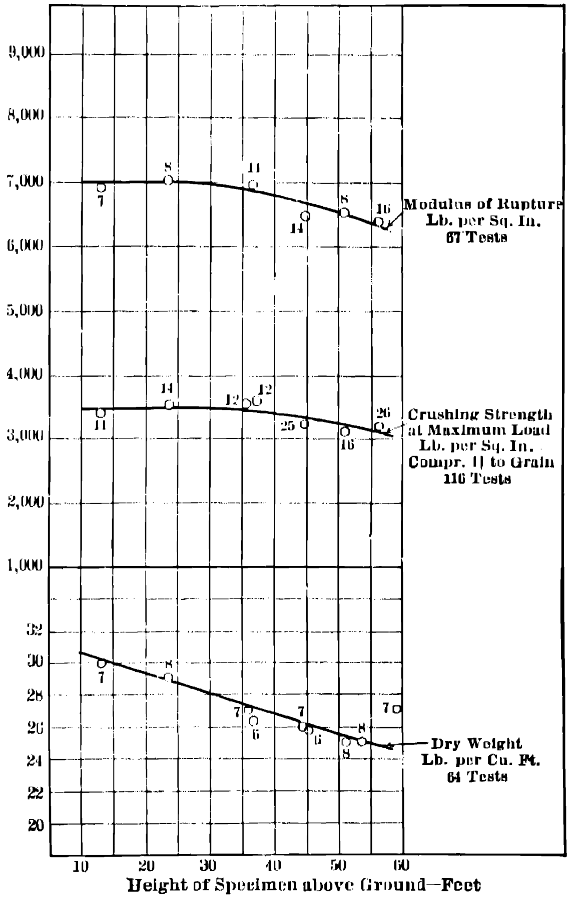


FIG. 11.—Relation of Strength Values to Height in Tree. Specimens were small clear pieces of green western larch. (*Bull.* No. 122, Forest Service.)

240. The Influence of Defects on Mechanical Properties.—Defects such as knots, checks, shakes, and inclined grain are limited in structural grades of timber, since they are a principal cause of variation in mechanical properties. The discrepancies in strengths of large and small specimens and the variation in properties of test-pieces of the same wood are largely due to defects. *The magnitude of the influence of defects is determined by their character, size, and location,* and these factors are given consideration in the limitations for various structural grades.

Knots in heavy beams and posts which do not run directly through the member, or knots running normal to the top of a beam, reduce strength in direct proportion to their size. When knots run directly through joists and beams near the top and bottom surfaces in the mid-half of the length, their weakening effect is approximately in the ratio of twice the diameter to the depth of member. Knots near the ends of beams are less harmful than when near the middle, hence larger knots may be permitted in the end zones than near mid-length. Since grain distortion and shrinkage strains are greater around large knots than around small knots, the maximum permitted size is varied with the width of the face of the timber containing the defect. The distribution and the sum of the knot diameters in the face of a post or beam also affect strength and are limited in grading rules.

From numerous compression parallel-to-grain tests on 6 by 6-in. wood prisms containing sound knots of various sizes, the comparisons shown in Table 6 were drawn from *Bulletin* 108, Forest Service. These data show

TABLE 6.—EFFECT OF KNOTS ON COMPRESSION PROPERTIES OF WOOD

Species.	Kind of Knot.	Diameter of Knot (Inches).	Percentages of Results Based on Compression Tests of Clear Specimens for		
			Elastic Limit.	Crushing Strength.	Modulus of Elasticity.
Douglas Fir.......	Pin	0–½	95	94	106
	Standard	½–1½	87	86	90
	Large	Over 1½	78	78	71
Western Larch....	Pin	0–½	112	104	119
	Standard	½–1½	98	89	100
	Large	Over 1½	98	85	94
Western Hemlock..	Pin	0–½	96	97	100
	Standard	½–1½	94	91	97
	Large	Over 1½	86	83	81

that the strength and stiffness of short compression members may be reduced 15 to 30 per cent by the presence of knots 1½ in. or over in diameter. In long columns, however, the effects of knots on stiffness is immaterial, hence the Euler loads are not reduced by the presence of knots.

Other tests by the Forest Products Laboratory have shown that knots have little effect on the elastic limits and stiffnesses of beams, but they decrease the modulus of rupture. Consequently knots in beams will adversely affect ultimate strength and toughness. Sound knots near the neutral plane have little influence on the shearing strengths of beams.

Shakes and checks are most harmful to strength when they follow the neutral plane of a beam or run diagonally across the tension side of it. In the first case they weaken the resistance to horizontal shear, and in the second case they lessen the tensile strength.

In seasoned timber shakes and checks are more pronounced than in green timber. Hence in grading rules for structural timbers the severity of the limitation on the proportion of the width of face occupied by check or shake varies with the grade and condition when inspected.

Inclination of grain to the axis of a beam less than 1 : 40 has little effect on strength. For greater slopes the strength is considerably reduced. Forest Products Laboratory tests indicate that grain slopes of 1 : 20 cause a decrease in beam strength of about one-eighth, 1 : 15 about one-fourth, 1 : 11 about three-eighths, and 1 : 8 about one-half. For posts, grain inclined 1 : 15 reduces strength about one-eighth, 1 : 11 about one-quarter, 1 : 8 about three-eighths, and 1 : 6 about one-half.

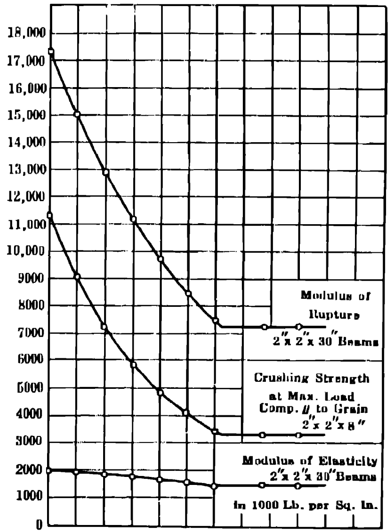


FIG. 12.—Effect of varying degrees of moisture upon the strength of small, clear specimens of western (known to trade as West Coast) hemlock. (*Bulletin* 115, U. S. Dept. of Agriculture.)

241. The Effect of Moisture on Mechanical Properties.—Variations in the moisture content of the cell walls are accompanied by large changes in the strength and stiffness of wood. These effects are most noticeable in small, clear pieces which season with great rapidity. On account of the slowness with which large structural timbers dry it is, however, unsafe to count on any increase in strength due to air-drying of such members. After years of seasoning, large timbers may lose enough water to effect an increase in tensile and compressive strength and in stiffness, but defects arising from shrinkage stresses often cause a decrease in the resistance to horizontal shear stresses. In kiln-drying the normal increase in strength due to loss of moisture is often nullified by case-hardening, a condition which prevents complete drying of the piece and produces internal stresses. Since, however, pieces less than 4×4 in. in cross-section may be considerably strengthened and stiffened by proper drying, the magnitude of the influence of moisture on these properties will next be considered.

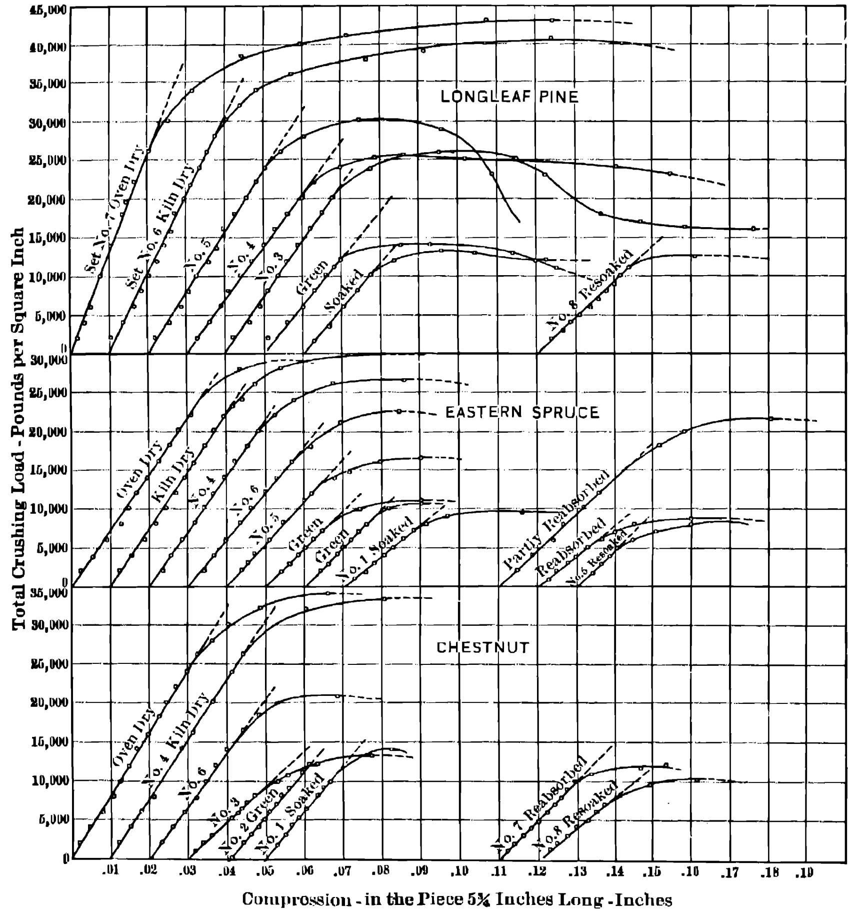


FIG. 13.—Stress-deformation Diagrams for Compressive Tests Parallel to the Grain in Woods Varying in Moisture Content from Wet to Oven Dry Conditions. (*Bull.* No. 70, Forest Service.)

The mechanical properties of wood are not materially affected by a reduction in the moisture content until the fiber-saturation point is reached. Further drying causes a large proportionate increase in strength and stiffness. These statements are supported by typical evidence in Fig. 12. Fig. 13 shows the effects of variations in moisture content on the shapes of the compressive stress-deformation curves for several kinds of wood. All specimens used in securing the data for the above figures were of clear material 2×2 in. in cross-section. Compression test-pieces were 5¾ in. long; bending specimens were loaded at the center over a 3-ft. span.

A summary of the effects of moisture on the strength and stiffness of small, clear sticks of certain woods is contained in Table 7.

TABLE 7.—THE STRENGTH AND STIFFNESS OF AIR-DRY AND KILN-DRY WOOD EXPRESSED IN TERMS OF GREEN MATERIAL

(Tiemann, in *Bull.* No. 70, Forest Service)

Species.	Ultimate Strength Ratios.*				Stiffness Ratios.			
	Compression parallel to grain.		Cross Bending.		Compression parallel to grain.		Cross Bending.	
	Kiln-dry †	Air-dry †	Kiln-dry †	Air-dry ‡	Kiln-dry †	Air-dry ‡	Kiln-dry †	Air-dry. ‡
Longleaf pine....	2.9	1.7	2.5	1.5	1.6	1.2	1.6	1.1
Red spruce......	3.7	2.4	2.8	1.9	2.3	1.6	1.4	1.2
Chestnut........	2.8	1.8	2.1	1.6	1.4	1.2	1.4	1.2
Loblolly pine, heartwood.....	3.0	2.0	.....	.....	1.9	1.4	.....	.....
Douglas fir......	2.6	1.7	.....	.....	1.5	1.3	.....	.....

* Ratios for the elastic limit are approximately the same.
† Kiln-dry = 3½ per cent moisture.
‡ Air-dry = 12 per cent moisture.

Since wood rarely remains as dry as when taken from the kiln, the tabulated values for air-dry material are of more general application than those given for the dryer condition. The table well shows that the strength of small sticks of air-dry wood may be 50 per cent or more and the stiffness 10 per cent or more than the corresponding values for green material.

242. Effect of Temperature on Strength of Wood.—The effects of temperature on wood are dependent upon the moisture content. Dry wood expands slightly when heated, while wet wood shrinks owing to the evaporation of moisture.

The linear coefficient of thermal expansion parallel to the grain is approximately 0.000006 for beech, walnut, maple, elm, and chestnut; 0.000005 for oak and pine; 0.000004 for poplar, mahogany and fir; and 0.0000026 per deg. C. for boxwood. In radial direction, the coefficient for the species mentioned above is from 5 (for chestnut) to 15 (for fir) times the value given for longitudinal expansion.

Very high temperatures such as used in vulcanizing slightly weaken dry wood. Freezing somewhat increases both the strength and stiffness of wood.* If wood is kept moist during the heating process it is rendered very pliable and is weakened. The results of a large number of tests on the effect of various drying and steaming treatments on wood were reported by Tiemann in the *Lumber World Review*, Apr. 10, 1915.

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* See *Bull.* No. 70, Forest Service.

From this report, Table 8 has been abstracted. The results show that steaming green wood under high temperatures and pressures greatly weakens it. Air-dried wood subjected to temperatures above 330° F. and steam pressures of 90 lb. per square inch was also weakened but to a less extent than the soaked wood.

TABLE 8. THE WEAKENING EFFECT OF VARIOUS DRYING PROCESSES ON THE CRUSHING STRENGTH OF 2×2-IN. WOOD PRISMS

(Tiemann, in *Lumber World Review*, Apr. 10, 1915)

Treatment.	Kind of Wood.	* Reduction in Strength in Per Cent of Normal when		
		Soaked, Treated. Soaked, Tested.	Air-dried, Treated. Air-dried 1 Year, Tested.	Soaked, Treated. Air-dried 1 Year, Tested.
Dry air, 145° F., 25 days	White ash	−23.4	0	0
26 days	Loblolly pine	−21.0	0	
30 days	Red oak	− 7.9	+16.3	
Saturated steam 212° F., 1 hr.	White ash	−12.5	0	0
	Loblolly pine	−24.8	0	
	Red oak	+13.8	− 4.4	+ 1.1
Saturated steam 212° F., 4 hr.	White ash	−10.3	0	0
	Loblolly pine	−19.7	0	
	Red oak	− 1.5	− 2.4	
Saturated steam 90 lb./in.², 331° F., 5 min	White ash	−24.8	4	0
15 min	Loblolly pine	−27.3	− 9	
5 min	Red oak	−44.5	−49.1	−13.7
Saturated steam 90 lb./in.², 331° F., 1 hr.	White ash	−44.7	−27	0
4 hr	Loblolly pine	−36.6	−42	
3½ hr	Red oak	−39.9	−61.3	−24.9
Superheated steam 0 lb./in.², 331° F., 6 hr	White ash	−11.9	0	−3
274° F., 4 hr	Loblolly pine	−18.0	0	
10 lb./in.², 274° F., 4 hr	Red oak	−49.8	−60.0	

* The minus sign indicates a loss in strength.

Prof. W. K. Hatt * states that a high degree of steaming reduces the strength and the spike-holding power of the wood. The safe limiting conditions for steaming depend upon the quality of the wood, the thoroughness of seasoning, the steam pressure, and the duration of steaming. He states that loblolly pine should not be steamed at pressures above 30 lb. per square inch for more than four hours, or 20 lb. per square inch for more than six hours.

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* *Circular* No. 39, Forest Service.

243. The Effect of Preservatives on Strength.—Experiments made at the Forest Products Laboratory * show that creosote oil in itself is not injurious to the strength of timber, but excessive heat or pressure during the steaming and impregnation processes may injure strength considerably. From a boiling treatment (see Art. 220), on Douglas fir timbers, both green and air-seasoned stringers lost about one-third of their normal strength. More recent tests by the Forest Service and others have shown that the boiling-under-vacuum method of treatment produces Douglas fir timber markedly superior to that treated by the ordinary boiling or steaming and boiling processes. In the Forest Service tests on 8×16-in. stringers the temperature approximated 190° F., duration of boiling-under-vacuum 21 to 22 hours, pressure period 2 to 3 hours, and maximum pressure was about 125 lb. per sq. in. The ratios of strength of treated to strength of normal timbers varied from 87 to 94 per cent. The ratio was 93 per cent for the unseasoned and 90 per cent for the timbers seasoned before treatment. The tests indicated that the reduction in strength was less as the size of piece, temperature, length of boiling period, and pressure were reduced. However, the best combination of these variables still awaits a thorough investigation.

Zinc chloride solutions of the strengths commonly used in treating do not seriously weaken timber, but apparently do render it somewhat more brittle under impact.

244. Fire-killed Douglas Fir.—From the results of over 400 tests on beams of structural size and several hundred tests on smaller specimens,† it appears that fire-killed Douglas fir, if sound, is practically as strong and just as stiff as material gotten from growing trees. If such timber has stood for several years after the fire, it is likely to be badly eaten by beetles, borers, and fungi. Consequently careful inspection should be made to detect evidences of such deterioration before using fire-killed Douglas fir.

245. Effect of Bleeding on Strength of Longleaf Pine.—The wood of pine trees which have been bled for turpentine is just as strong as that of unbled trees. This statement is based upon the results of over 1300 tests made by the Forest Service (*Cir.* No. 12) on air-dry material. Furthermore, these tests show that neither the shrinkage nor the specific weight are affected by bleeding; and that the resin loss, confined to the sapwood, is insufficient to affect the durability of the wood. Other tests indicate that the strength of longleaf pine is independent of the resin content.

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* See *Circular* No. 39, of Forest Service, and *Bulletin* No. 286 of U. S. Dept. of Agric.

† J. B. Knapp in Forest Service *Bull.* No. 112.

STRENGTH OF NAILS AND WOOD JOINTS

246. Holding Force of Nails, Screws, and Spikes.—*Nails.*—A large number of tests at the Forest Products Laboratory indicate that the withdrawal load, P, for common nails or spikes per inch of embedment driven into side grain in seasoned wood approximates $P=6900\rho^{2.5}d$; where $\rho=$ specific gravity and $d=$nail diameter in inches. The safe quiescent load suggested for most species is $P/6$; for southern pine $P/8$ is preferable.

Resistance to withdrawal is increased from 90 to 200 per cent by chemically etching nails and increased about 40 to 50 per cent when cement-coated nails are used in softwoods. Barbed nails, nails with shanks longitudinally or spirally grooved, square or triangular in section, have superior resistance to withdrawal to common nails. When common nails are driven into green wood they usually lose part of their withdrawal resistance if the wood seasons; barbed and grooved nails usually retain most of their holding force. Nails with blunt tapered points and nails driven into lead holes exhibit greater holding forces than common nails and nails driven without lead holes. In softwoods the holding force parallel to the grain is only half to three-fourths the value normal to the grain. In hardwoods the direction of driving has little effect on the holding force.

Screws.—Tests by the Bureau of Standards show that the withdrawal force, P, for common wood screws per inch of length when inserted normal to the grain in seasoned wood approximates $P=10{,}200\rho^2d$. In this expression it is assumed that the screws are of common lengths, embedded at least two-thirds of their lengths, and inserted in lead holes having a diameter about 70 per cent of the root diameter of the screw when placed in softwoods and 90 per cent when in hardwoods. A factor of safety of 6 is suggested for quiescent loads. Screws inserted parallel to the grain can carry about three-fourths of the foregoing values if splitting is avoided.

Railroad Spikes.—In Table 9 are given results of tests made at the University of Illinois to determine the holding force of ordinary spikes and screw spikes in various woods. The common spikes were $5\frac{1}{2}$ and 6 in. long by $\frac{9}{16}$ to $\frac{5}{8}$ in. square; they were fairly smooth. The screw spikes varied from 5 to $5\frac{1}{2}$ in. in length and had a diameter at root of thread of $\frac{21}{32}$ to $\frac{22}{32}$ in. The thread projected $\frac{1}{8}$ to $\frac{3}{16}$ in. and the pitch was $\frac{1}{2}$ in. Spike holes were bored $\frac{11}{16}$ in. in diameter, thereby insuring a tight fit. The results in the table are corrected for a uniform depth of 5 in. Other tests made to determine the effect of depth of penetration on strength indicated that these factors were directly proportional. Blunt-pointed and bevel-pointed spikes were shown to be slightly superior to chisel-pointed spikes. Common spikes when redriven had about 60 to 80 per cent of the resistance of newly driven spikes.

Not only is the holding force of screw spikes much greater than that

TABLE 9.—RELATIVE HOLDING POWER OF SCREW SPIKES AND ORDINARY SPIKES IN SEVERAL TIMBERS

(*Bull.* No. 6, Engr. Expt. Sta., University of Illinois)

Kind of Tie.	Kind of Spike.	Resistance in Pounds for			Relative Resistances.		
		⅛-in. Pull.	¼-in. Pull.	Max. Resist.	⅛-in. Pull.	¼-in. Pull.	Max. Resist.
Water oak......	Ordinary..	2870	5,730	6,780	100	100	100
	Screw....	4888	9,180	12,190	170	160	179
Black oak......	Ordinary..	2910	5,890	7,230	100	100	100
	Screw....	4760	10,420	14,110	164	177	203
Red oak........	Ordinary..	2950	5,350	7,730	100	100	100
	Screw....	4900	10,400	13,560	166	194	176
White oak......	Ordinary..	3510	5,950	7,870	100	100	100
	Screw....	6250	11,900	12,630	178	200	188
Ash............	Ordinary..	3570	5,200	7,730	100	100	100
	Screw....	5700	10,470	12,760	162	200	165
Beech..........	Ordinary..	2600	5,490	8,840	100	100	100
	Screw....	6450	13,140	16,230	248	221	238
Elm...........	Ordinary..	2380	5,580	7,500	100	100	100
	Screw....	5120	10,090	13,690	215	181	183
Poplar.........	Ordinary..	2830	5,290	5,670	100	100	100
	Screw....	3880	6,210	7,490	137	117	132
Chestnut.......	Ordinary..	2850	4,070	5,200	100	100	100
	Screw....	3690	6,340	8,700	129	155	167
Sweet Gum......	Ordinary..	3230	4,120	5,300	100	100	100
	Screw....	5430	7,710	8,280	167	162	156
Loblolly pine....	Ordinary..	2920	3,500	4,300	100	100	100
	Screw....	5750	9,050	10,620	197	258	247

of plain spikes, but their resistance to lateral thrust is also considerably higher. Prof. W. K. Hatt * found that the lateral resistance of screw spikes was 1.2 to 2.4 times the resistance of plain spikes similarly tested. No support was provided for the head of the spike in these tests. In timber treated with crude oil the holding force of plain spikes is considerably less than in untreated timber or in timbers treated by other commercial processes. For shortleaf pine treated with crude oil, Hatt found the holding force of plain spikes to be only 45 per cent. and of screw spikes 73 per cent. of the values obtained for the respective spikes driven in untreated wood.

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* See *Bull.* No. 124, Am. Ry. Engr. Assn.

247. The Strength of Joints.—*Nailed and Screwed Joints.*—Extensive tests by the Forest Products Laboratory resulted in the formula for the safe lateral load for wire nail joints, $P = Kd^{3/2}$, in which P represents the safe lateral load in pounds per nail, d the diameter of the nails, and K a constant depending on species and condition of wood. With a factor of safety of 6 and a moisture content of 15 per cent, the values of K given in Table 10 apply. With reasonable spacing, the strength of the joint is in proportion to the number of nails used. For safe lateral loads on wood screws under conditions similar to the above, the Laboratory recommends the equation $P = K_s d^2$, in which d is the diameter of shank of the screw, with the values of K_s given in Table 10 and a penetration into the block receiving the point of 7 or more diameters, the corresponding loads will have a factor of safety of about 6 and the joints would be expected to slip 0.007 to 0.01 in.

TABLE 10.—VALUES OF CONSTANTS K AND K_s FOR WOOD JOINTS

Species of Wood	K	K_s
Cedar, white; Hemlock, eastern; Pine, lodgepole, sugar, white; Spruce, red, Sitka, white	900	2100
Cedar, red; Cypress; Hemlock, western; Pine, Norway; Redwood; Tamarack	1125	2700
Douglas fir (coast region); Larch, western; Pine, southern yellow	1375	3300
Aspen; Basswood; Chestnut; Cottonwood; Poplar	900	2100
Ash, black; Elm, American; Gum; Maple, soft; Sycamore	1250	2900
Ash, white; Beech; Birch, sweet, yellow; Elm, rock; Hickory; Locust; Maple, hard; Oak; Walnut	1700	4000

Bolts and Connectors.—In the *Wood Handbook* the Forest Products Laboratory gives much valuable test data and information for the design of wood joints fastened by bolts and by various types of modern ring or plate connectors. In the design of bolted connections not only is the safe bearing stress for the timber a point to be considered but also the ratio of length of the bolt in main timber to diameter of bolt is an important factor when greater than 4. The connectors are partially bedded in the pieces to be joined and act much like rigid dowels. Bolts placed in oversize holes are centered in such connectors to aid in assembling and maintaining tight joints.

Glued Joints.—The efficiency of glued joints depends on the kind and condition of the wood, the kind and condition of the glue, method of gluing type of joint and method of conditioning it, and the protection given the joint. Among the woods that are easiest to glue are western red cedar, chestnut, white fir, redwood, and spruce; whereas beech, birch, gum, and hickory require special treatment in order to obtain good results.

Animal, casein and resin glues all find use in gluing woodwork. Animal glues give best results when kept warm, set quickly without stain, and are much used for furniture, veneer, and millwork. Casein glues are mixed with cold water, set quickly, stain some woods badly, dull markedly woodworking tools, and are used in gluing lumber, veneer, plywood, air craft, and automobile bodies. They are moderately durable under damp conditions. The most commonly used synthetic-resin glues are the phenol-formaldehyde and urea-formaldehyde types. Both are thermosetting. They are available in the form of dry film, dry powder, or in solution. When hot-pressed at 250° F. they are durable under severe exposure. Resin glues are used primarily in veneer and laminated wood construction.

The moisture content of wood to be glued should be less than 15 per cent; the optimum is slightly less than the content which will obtain under service. A uniform film of glue free from air bubbles or dirt and complete contact between the surfaces joined are essential to strong joints. Plain joints between side grain surfaces can be made to develop the strength of the wood in longitudinal shear, in tension across grain, and in cleavage. By using a scarf joint having a slope with the grain not greater than 1 to 15 the tensile strength of the wood parallel to the grain can be equaled; with a butt joint only one-fourth of this strength can be secured.

Care should be taken to avoid finishing edge joints until the glue moisture has been dissipated. Artificial drying of glued wood should be carefully controlled. For moisture contents under 12 per cent, well-glued wood joints are permanent. The durability of joints may be materially increased by impregnation with preservatives.

248. Plywood signifies glued wood panels usually made of two or more thin layers of wood with the grain of one or more layers at an angle of 90 deg. with the others. Usually 3, 5, or 7 plies are glued in such manner that the grain direction of the bands is balanced with respect to the core layer in order to avoid as far as possible warping due to shrinkage and swelling. Panels are commonly made 4 ft. wide and 8 ft. long and in thicknesses of $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, and $\frac{3}{4}$ in.

Plywood does not check or split so easily when nailed or screwed and possesses better shear strength than solid wood if buckling is prevented.

For computing the ultimate bending moment, M, of plywood, the Forest Products Laboratory uses $M = KSI/c$ where S is the modulus of rupture of the solid wood, I the moment of inertia of only the plies with grain parallel to the span, c the distance from the neutral axis to the outer fiber of the outermost ply having grain parallel to span, and K is a constant. For plywood with 3 or more plies having face-ply grain parallel to span, or with 5 or more *plies having face-ply grain perpendicular to span, $K = 0.85$; with 3 plies and face-ply grain normal to span, $K = 1.5$.*

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WORKING STRESSES AND GRADING RULES

249. Working Stresses.—From the results of extensive and carefully conducted tests the Forest Products Laboratory has compiled a *Guide to the Grading of Structural Timbers and the Determination of Working Stresses.* Both the American Society for Testing Materials and the American Railway *Engineering Association have based their specifications for the different structural grades of timber on the limitations proposed by the* Laboratory regarding stresses and defects. In the present specifications for structural timber issued by these bodies timbers are separated at the mill into grades in accordance with their inherent defects. From the laboratory data the safe strength of each grade under continuously dry conditions is known and used as the characteristic designation for that grade. Thus *1600f*, applied to a timber beam, indicates that the member can carry safely under dry conditions a maximum fiber stress of 1600 lb. per sq. in.; likewise *1300c* signifies that the member, as a short column, can safely carry a load of 1300 lb. per sq. in. applied parallel to the grain.

The terms *dense* and *close-grained* are applied to timbers of certain species, as indicated in Sec. 14 and 15 of the grading rules in Art. 250.

Exposure is divided by the Laboratory into three degrees of severity: (*a*) continuously dry, as in protected locations of low humidity; (*b*) occasionally wet but quickly dried, as in bridges, trestles, grandstands, and exposed frames; (*c*) more or less continuously damp or wet, as exposed to waves or tides, in contact with ground or wet structures. Roughly, fiber stresses in bending and in compression parallel to the grain for condition (*b*) should not exceed $\frac{7}{8}$ of values permitted for condition (*a*); and for condition (*c*) they should not exceed $\frac{3}{4}$ the values for (*a*). For compression perpendicular to the grain the stress ratios for conditions (*b*) and (*c*) should not exceed 0.7 and 0.6, respectively.

Impact stresses when less than 100 per cent of the live load need not be considered, if the working stresses are properly used.

Horizontal shear stress values are the maxima permitted at the neutral axis in beams. In calculating the shear near the end of a beam the loads concentrated between the ends and a point three times the depth of the beam from the end may be considered acting at that point. For moving loads on stringers of highway or railway bridges, however, it is permissible, in calculating the shear at one end, to ignore the wheel loads between the end and a point three times the depth of the beam from that end provided the remainder of the span is assumed loaded to produce maximum end shear.

Shear stresses in joint details may be increased 50 per cent above the values permitted for horizontal shear in beams, Table 12.

Modulus of elasticity values given in the tables are for loads of short duration. For calculating the deflections of beams under continuous loads, it is advisable to use one-half of the tabulated values to allow for sag due to continued loading.

The working unit stresses for compression parallel to the grain in Table 12 are for posts and struts with ratio of unsupported length to least dimension (l/d) not over 10. These values should also be used in calculating end bearing areas for compression members, since short struts are likely to fail at the ends due to differences in moisture content.

For columns of intermediate length a fourth-power parabola and for long columns a tangent Euler curve provide a combination of formulas which, the Forest Products Laboratory tests have demonstrated, represent the strength-slenderness-ratio relationship. The parabolic formula for columns of intermediate length is

$$\frac{P}{A}=S\left[1-\frac{1}{3}\left(\frac{l}{Kd}\right)^4\right], \text{ between } \frac{P}{A}=S \text{ and } \frac{P}{A}=\frac{2S}{3},$$

where P = safe load in pounds, A = cross-sectional area in square inches, S = working unit stress in compression parallel to grain for short column (Table 12), l = unsupported length in inches, d = least dimension in inches, $K=\frac{\pi}{2}\sqrt{\frac{E}{6S}}$ is the abscissa of the point of tangency with the Euler curve, E = modulus of elasticity (see Table 12). Values of K for different species are given in Table 12.

The tests have demonstrated that the detrimental influences of defects on the strengths of columns decrease as the ratio l/d increases until $l/d=K$. For longer columns the tests show that the Euler formula is accurate for pin end columns. To obtain safe loads, a factor of safety of 3 is recommended. With the available data and usual conditions, the laboratory does not find it advisable to increase the permitted loads for square end columns beyond those recommended in the following formula for columns with pin ends.

The Euler formula for long columns with a factor of safety of 3 is

$$\frac{P}{A}=\frac{\pi^2 E}{36(l/d)^2} \text{ between } l/d=K \text{ and } l/d=50.$$

Tension.—Where wood is used in direct tension the fiber stresses permitted in bending may be employed safely, provided joint details are properly designed. When the grades of joists or beams are used to carry tension, as in bottom chords of trusses, defects may be allowed to increase in size toward the ends of the members due to the gradual imposition of stress through splice plates.

Limitation on Defects.—In the joist and plank grades restrictions are made so that allowable fiber stresses may be applied to either broad or narrow faces of these members. For material 5 in. and thicker loaded on the broad face, the knot requirement for the broad face is the same as given in the rules for the narrow face. Timbers of square or nearly square section which are to be subjected to bending should be selected on the basis of beam and stringer grading rules, but care should be exercised to see that knot restrictions are applied to the proper faces.

In stringers of two-span length subject to moving loads the same restrictions should be imposed on defects occurring in middle two-thirds length as apply to the middle third of the length of a single span stringer.

Basis of Working Stresses.—In obtaining the tabulated working stresses the Forest Products Laboratory considered both the elastic limit and ultimate strength, but adopted the latter as the more reliable basis for determining safe working stresses. The factors of safety vary with the duration of stress. Under the recommended stresses for timbers in dry locations, the average timber in a building has a factor of safety of 6 for impact loading, 4 for a load lasting 5 minutes, and 2¼ for a loading of long duration. Approximately 1 per cent of the pieces of very light weight carrying maximum defects permitted in a given grade would probably break if stressed 50 per cent above the recommended value for 10 years. New timbers in bridges have factors of safety about 15 per cent higher than the above.

The recommended working stresses are based upon the strength of the clear green wood of the given species and are varied in accordance with the following: Extreme fiber stresses in bending are varied with grade, type of exposure, and size of piece; horizontal shear stresses, with grade; stresses in compression parallel to grain, with grade and exposure; stresses in compression perpendicular to grain, with exposure. Modulus of elasticity values are considered constant for all grades, exposures, and sizes. In the highest stress grades, the allowable extreme fiber stresses range from 75 to 94 per cent of the basic stresses of green clear wood.

250. Grading Rules.—As a typical example of modern timber specifications, the general requirements for structural beams and timbers is inserted. These are followed by Table 11, which contains defect restrictions that these structural timbers must meet in order to be included in the stress grade *1800f*. For other stress grade requirements for joists and planks, beams and stringers, and posts and timbers consult the A.S.T.M. *Standards* or the A.R.E.A. *Manual*. A résumé of the stress grades with size requirements and working stresses is appended in Table 12.

EXTRACTS FROM STANDARD SPECIFICATIONS FOR STRUCTURAL WOOD JOIST AND PLANK, BEAMS AND STRINGERS, AND POSTS AND TIMBERS

(See A.S.T.M. Designation: D 245–37.)

General Requirements

Applying to All Stress-Grades and Items

Manufacture.—1. All material shall be well-manufactured.

Quality of Wood.—2. No piece of exceptionally light weight is permitted.

Decay.—3. Only pieces consisting of sound wood, free from any form of decay, are acceptable, unless otherwise specified.

Slope of Grain.—4. Slope of grain shall be measured over a distance sufficiently great to determine the general slope, disregarding slight local deviations. Within the middle half of length of piece, slope of grain shall not be steeper than specified.

Holes.—5. Knot holes and holes from causes other than knots are measured and limited as provided for knots.

Cluster Knots.—6. Cluster knots and knots in groups are not permitted.

Knots in Joist and Plank.—7. (*a*) *Knots on Narrow Faces.*—Size of knot on a narrow face is taken as width between lines enclosing knot and parallel to edges of piece. The only knots measured on narrow faces, except spike knots which cross the corners of side-cut pieces, are those that do not show on wide faces.

(*b*) *Knots on Wide Faces.*—Size of knot on a wide face is the average of its largest and smallest diameters. A spike knot which crosses a corner of a side-cut piece and contains the intersection of the adjacent faces, or which extends entirely across a face of a piece, shall be measured only on its end or ends, between lines parallel to the edges of the piece.

(*c*) *Permissible Increase in Knot Sizes.*—Size of knots on narrow faces and at edges of wide faces may increase proportionately from size permitted in middle third of length to twice that size at ends of piece. Size of knots on wide faces may increase proportionately from size permitted at edge to size permitted along center line.

(*d*) *Sum of Knots.*—Sum of sizes of all knots within middle half of length of any face, measured as specified by paragraph (*a*) or (*b*) for the face under consideration, shall not exceed four and one-half times the size of largest knot allowed on that face.

Knots in Beams and Stringers.—8. (*a*) *Knots on Narrow Faces.*—Size of knot on a narrow face is taken as width between lines enclosing knot and parallel to edges of piece, except that when a knot on a narrow face extends into the adjacent one-fourth of the width of a wide face its least dimension is taken as its size.

(*b*) *Knots on Wide Faces.*—Size of knot on a wide face is its smallest diameter. Knots at edges of wide faces are limited to same sizes as on narrow faces but are measured according to this paragraph.

(*c*) *Permissible Increase in Knot Size.*—Size of knots on narrow faces and at edges of wide faces may increase proportionately from size permitted in middle third of length to twice that size at ends of piece, except that size of no knot shall exceed size permitted along center line of wide face. Size of knots on wide faces may increase proportionately from size permitted at edge to size permitted along center line.

(*d*) *Sum of Knots.*—Sum of sizes of all knots within middle half of length of any face, measured as specified by paragraph (*a*) or (*b*) for the face under consideration, shall not exceed four times the size of largest knot allowed on that face.

Knots in Posts and Timbers.—9. (*a*) *Knots on Either Face.*—Size of a knot is half the sum of its largest and smallest diameters. A spike knot which crosses a corner of a side-cut piece and contains the intersection of the adjacent faces, or which extends entirely across a face of a piece, shall be measured only on its end or ends, between lines parallel to the edges of the piece.

(*b*) *Sum of Knots.*—Sum of sizes of all knots in any 6 in. of the length of piece, measured as specified by paragraph (*a*), is not permitted to exceed twice the maximum permissible size of knot. Two knots of maximum permissible size are not allowed in same 6 in. of length on any face.

Shakes, Checks, Splits in Joist and Plank and Beams and Stringers.—10. (*a*) Shakes, checks, and splits, where permitted in the grade specified later in these specifications, are measured at ends of piece. Only those within middle half of height are considered. (Height equals width of wide face.) Size of shake is distance between lines enclosing shake and parallel to wide faces of piece. Permissible size is determined by width of narrow face of piece.

(*b*) Checks and splits are measured and limited in same way as shakes. The following limitations apply to both ends but only within middle half of height of piece and within three times height from end. (Height equals width of wide face.) Size of checks within this portion of piece shall be taken as their estimated area, along horizontal section showing maximum area, divided by three times height of piece (Note). When checks on two parallel faces are opposite or approximately so, sum of their sizes is taken. Sum of sizes of shakes, checks, and/or splits shall not exceed permissible size of shake.

(*c*) Checks extending entirely across end within middle half of height shall not extend into piece at center of width of end a distance greater than size of allowable shake.

Shakes, Checks, Splits in Posts and Timbers.—11. (*a*) Shakes, checks, and splits, where permitted in the grade specified later in these specifications, are measured at the ends of the piece. Size of a shake is distance between lines enclosing shake and parallel to a pair of opposite faces.

(*b*) Checks and splits are measured and limited in the same way as shakes. Size of checks within three times width of piece from either end shall be taken as their estimated area, along the longitudinal section showing maximum area, divided by three times width of piece (Note). Sum of sizes of shakes, checks, and/or splits shall not exceed the permissible size of shake.

(*c*) Checks extending entirely across end shall not extend into piece at center of width of end a distance greater than size of allowable shake.

NOTE.—A practical method of inspection in the field to determine the size of checks and splits under the above specifications is as follows:

The size of checks within the specified portion of the piece shall be taken as the sum of seven depth measurements, one on the end and three on each side, divided by three. Each measurement shall represent the greatest depth of any check within the center half of the height; the measurement on the end shall be taken at the center of the width, and the three measurements on each side shall be taken at distances of one, two, and three times the height of the piece from the end in joist, plank, beams and stringers, and the width of the piece from the end in posts and timbers. Each measurement shall be determined by the penetration into the piece of a probe $\frac{1}{64}$ in. in thickness and $\frac{1}{4}$ in. in width.

MBER DARD ST AND ADDITIONAL REQUIREMENTS
AL BEA

A sible to locate it — *hen Heartwood or Wane, and Where Density and Close*
in. on an approxi — *Grain Are Required*

F 3 in. in thickness·········
hickness. ugh thick — 12. Where heartwood material is desired, it shall be
speci*ir, or Redwood.*— it of piece ········ or percentage of heartwood on the girth, or on each face,
side ··· an six nor more or S2S. ·· point where the greatest amount of sapwood occurs.
Fo ior more than th ······ re treated, there shall be no heartwood requirement and
the am at right angle ugh width of pieces is ot be limited.
Wan ········· s not desired, the specifications should state "Square
Edge." r. ········· or farthest f S2E. ·····

Densi ficiently to — 14. (*a*) *Dense Douglas Fir.*—Shall average on either
one end of ·· ce not less than six annual rings per inch in Douglas fir,
and, in add -in. porti tress-Grad more summerwood (the dark portion of the annual ring)
measured ov the 3-in ast di at a right angle to the annual rings, located as described
below. The th between summerwood and springwood shall be distinct.
Coarse-gra cluded by this rule shall be accepted as dense if averaging
one-half or mo l.

In boxed-hea ades and Speci line shall run from the pith to the corner farthest from the pith except, whe Douglas Fir (Co Longleaf or not representative, it shall be shifted sufficiently to present a fair average but ······ ained Dougla e from the pith to the beginning of the 3-in. portion of the line shall not be ch Longleaf or When the least dimension is 6 in. or less, the 3-in. portion of the line shall begin Red Redwo ance of 1 in. from the pith. When the least dimension is more than 6 in., the Red Cypre tion of the line shall begin at a distance from the pith equal to one-fourth the lea af Southe sion of the piece.

In side-cut pieces (Redwo f South present) the center of the 3-in. portion of the line shall be at the center of the end Redwo e piece. ar...

If a 3-in. portion of ypre line cannot be obtained, the measurement shall be made over as much of a 3-in. portion as is available.

In case of disagreement, two radial lines shall be chosen and the summerwood and number of rings shall be taken as the average on these lines.

(*b*) *Dense Longleaf or Shortleaf Yellow Pine.*—Shall average on either one end or the other of each piece not less than six annual rings per inch, and, in addition, one-third or more summerwood (the darker, harder portion of the annual ring), measured over the third, fourth, and fifth inches of a radial line from the pith. The contrast in color between summerwood and springwood shall be sharp and the summerwood shall be dark in color, except in pieces having considerably above the minimum requirement for summerwood.

Coarse-grained material excluded by this rule shall be accepted as dense if averaging one-half or more summerwood.

The radial line shall be representative of the average growth of the cross section. In case of disagreement, two radial lines shall be chosen, and the number of rings per inch and percentage of summerwood shall be taken as the average determined on these lines.

In boxed-heart pieces the measurement shall be made over the third, fourth, and fifth inches from the pith along the radial line.

In material containing the pith, but not a 5-in. radial line, which is l 300 har 22..
8 in. in section or less than 8 in. in width, that does not show over 16 so
s ion, the inspection shall apply to the second inch from the ith.
t es not show a 5-in. radial line, the inspection sha
fa he from the pith.

In cases where timbers do not contain the pith and it is impossible to locate it with any degree of accuracy, the same inspection shall be made over 3 in. on an approximate radial line beginning at the edge nearest the pith in timbers over 3 in. in thickness and on the second inch nearest the pith in timbers 3 in. or less in thickness.

Close Grain (where required).—15. *Close-Grained Douglas Fir, or Redwood.*—Shall average on either one end or the other of each piece not less than six nor more than twenty annual rings per inch in Douglas fir, or not less than ten nor more than thirty-five annual rings per inch in redwood, measured over 3 in. on a line at right angles to the annual rings located as described below.

In boxed-heart pieces the line shall run from the pith to the corner farthest from the pith except, when the line is not representative, it shall be shifted sufficiently to present a fair average but the distance from the pith to the beginning of the 3-in. portion of the line shall not be changed. When the least dimension is 6 in. or less, the 3-in. portion of the line shall begin at a distance of 1 in. from the pith. When the least dimension is more than 6 in., the 3-in. portion of the line shall begin at a distance from the pith equal to one-fourth the least dimension of the piece.

In side-cut pieces (pith not present) the center of the 3-in. portion of the line shall be at the center of the end of the piece.

If a 3-in. portion of the line cannot be obtained, the measurement shall be made over as much of a 3-in. portion as is available.

In case of disagreement, two radial lines shall be chosen and the number of rings shall be taken as the average on these lines.

Pieces of Douglas fir averaging five rings or more than twenty shall be accepted if containing one-third or more summerwood.

TABLE 11.—STRUCTURAL BEAMS AND STRINGERS *

f = Extreme fiber stress in bending in pounds per square inch for continuously dry locations.

1800 lb. f Structural Beams and Stringers

DENSE DOUGLAS FIR (COAST REGION)	DENSE LONGLEAF SOUTHERN PINE
DENSE DOUGLAS FIR (INLAND)	DENSE SHORTLEAF SOUTHERN PINE

Slope of Grain.—1 in 15.

Knots.—Maximum permissible size in inches:

Nominal Width of Face, in.	On Narrow Face, Middle Third of Length	At Center Line of Wide Face
5	$1\frac{1}{8}$ in.	.....
6	$1\frac{3}{8}$ in.	.....
8	$1\frac{5}{8}$ in.	$1\frac{7}{8}$ in.
10	$1\frac{3}{4}$ in.	$2\frac{1}{4}$ in.
12	$1\frac{7}{8}$ in.	$2\frac{5}{8}$ in.
14	$2\frac{1}{8}$ in.	$2\frac{7}{8}$ in.
16	$2\frac{1}{4}$ in.	$3\frac{1}{8}$ in.
18	.....	$3\frac{3}{8}$ in.
20	.....	$3\frac{1}{2}$ in.

Shakes, Checks, Splits:

	Width of Narrow Face When Green	Width of Narrow Face When Seasoned
120 lb. Shear Grade (Fir)	$\frac{1}{6}$	$\frac{1}{4}$
120 lb. Shear Grade (Pine)	$\frac{3}{10}$	$\frac{3}{8}$
120 lb. Shear G... th		
Wane	$\frac{1}{8}$ Width of any face	

...en beams ...t shall ...th.

* Table 11 illustrates one of many similar tables given in *A.S.T.M.*, Des. 247-37.

TABLE 12.—STANDARD SIZES, STRESS-GRADES, AND WORKING STRESSES FOR STRUCTURAL BEAMS AND STRINGERS, POSTS AND TIMBERS *

Standard Sizes:

	Beams and Stringers	Posts and Timbers
Nominal thicknesses	5 in. and thicker	
Permissible minimum rough thicknesses in not to exceed 20 per cent of pieces in any one shipment:		
5 and 6 in.	$\frac{3}{16}$ in. off	$\frac{3}{16}$ in. off
8 in. and wider	$\frac{1}{4}$ in. off	$\frac{1}{4}$ in. off
Dressed thicknesses, S1S or S2S	$\frac{1}{2}$ in. off	$\frac{1}{2}$ in. off
Nominal widths	8 in. and wider	5 in. and wider
Permissible minimum rough widths in not to exceed 20 per cent of pieces in any one shipment:		
5 and 6 in.	....	$\frac{3}{16}$ in. off
8 in. and wider	$\frac{1}{4}$ in. off	$\frac{1}{4}$ in. off
Dressed widths, S1E or S2E	$\frac{1}{2}$ in. off	$\frac{1}{2}$ in. off

Standard Stress-Grades and Working Stresses for Beams and Stringers:

(Continuously Dry Locations)

Grades and Species	Fiber Stress in Bending or Tension, lb. in.^{2}	Maximum Horizontal Shear, lb. in.^{2}	Compression Perpendicular to Grain, lb. in.^{2}	Modulus of Elasticity, lb./in.^{2}
1800 lb. *f* Dense Douglas Fir (Coast and Inland)	1800	120	380	1,600,000
1800 lb. *f* Dense Longleaf or Dense Shortleaf Southern Pine	1800	120	380	1,600,000
1600 lb. *f* Close-Grained Douglas Fir (Coast)	1600	100	345	1,600,000
1600 lb. *f* Dense Longleaf or Dense Shortleaf Southern Pine	1600	120	380	1,600,000
1600 lb. *f* Close-Grained Redwood	1600	80	267	1,200,000
1400 lb. *f* Tidewater Red Cypress	1400	120	300	1,200,000
1400 lb. *f* Oak	1400	120	500	1,500,000
1400 lb. *f* Dense Longleaf Southern Pine	1400	100	380	1,600,000
1400 lb. *f* Close-Grained Redwood	1400	80	267	1,200,000
1200 lb. *f* Dense Shortleaf Southern Pine	1200	100	380	1,600,000
1200 lb. *f* Close-Grained Redwood	1200	70	267	1,200,000
1100 lb. *f* Port Orford Cedar	1100	80	250	1,200,000
1100 lb. *f* Tidewater Red Cypress	1100	100	300	1,200,000
1100 lb. *f* Oak	1100	100	500	1,500,000
1000 lb. *f* Western Red Cedar	1000	100	200	1,000,000

Standard Stress-Grades and Working Stresses for Posts and Timbers:

(Continuously Dry Locations)

Grades and Species	Compression Parallel to Grain, Short Columns, lb./in.^{2}	Values of *K*
1300 lb. *c* Dense Douglas Fir (Coast and Inland)	1300	22.5
1300 lb. *c* Dense Longleaf or Dense Shortleaf Southern Pine	1300	22.5
1200 lb. *c* Tidewater Red Cypress	1200	20.3
1200 lb. *c* Close-Grained Douglas Fir (Coast)	1200	23.4
1200 lb. *c* Dense Longleaf or Dense Shortleaf Southern Pine	1200	23.4
1200 lb. *c* Close-Grained Redwood	1200	20.3
1100 lb. *c* Douglas Fir (Coast)	1100	24.4
1100 lb. *c* Oak	1100	23.7
1100 lb. *c* Close-Grained Redwood	1100	21.2
1000 lb. *c* Port Orford Cedar	1000	22.2
1000 lb. *c* Tidewater Red Cypress	1000	22.2
1000 lb. *c* Oak	1000	24.8
1000 lb. *c* Dense Longleaf Southern Pine	1000	25.6
1000 lb. *c* Close-Grained Redwood	1000	22.2
900 lb. *c* Port Orford Cedar	900	23.4
900 lb. *c* Dense Shortleaf Southern Pine	900	27.0
800 lb. *c* Western Red Cedar	800	22.7

* Compiled from tables and data in *A.S.T.M.*, Des. 245–37.

CHAPTER VII

BUILDING STONE *

251. Uses and Production.—We shall include under the head of building stone those stones which are used for ornamentation or for any form of masonry construction, as in foundations, retaining walls, buildings, bridges, pavements. In some of these constructions stone has been employed as a building material since the first Egyptian dynasty. The tombs and pyramids of Egypt, the excavated ruins of ancient Troy, remains of Grecian and Roman structures, and the many old monuments of stone scattered through England, France, Germany, and the Holy Land, all bear witness to the use which the ancients made of this material. The conditions which govern in the selection of stone for structural purposes are cost, fashion, ornamental value, and durability; although the latter property, it must be admitted, is frequently overlooked or disregarded. Cost is largely influenced by transportation charges, difficulties in quarrying and cutting, the ornamental features, and the durability of the stone. Color and arrangement, and shape of mineral constituents greatly influence fashion and ornamental value. Resistance to fire and power to withstand weather conditions—factors which are largely influenced by the mineral constitution of the rock—are the most important determinators of durability.

Suitable stone for structural purposes is widely distributed both in this country and abroad. Granite is found in large quantities in Canada, England, Scotland, Sweden, and Norway; within the United States, California, North Carolina, Vermont, Massachusetts, Georgia, and Maine lead in production. Limestone and marble are found abroad in Canada, Italy, England, Algeria, Germany, Belgium, France, and Austria. The following states lead in producing limestone: New York, Illinois, Ohio, Indiana, Michigan. Vermont, Georgia, Tennessee, Alabama, and Missouri provide most of the domestic marble. Sandstone is obtainable in Canada and Scotland; Ohio, Pennsylvania, West Virginia, New York, and California lead the states in production. Trap rock is produced principally in New Jersey, Connecticut, Oregon, Washington, and Pennsylvania. Slate is found abroad in Canada, England, and France: within the United

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* References: Merrill's *Stones for Building and Decoration* (out of print), Ries' *Building Stones and Clay Products* (out of print), Eckel's *Building Stones and Clays* (out of print), Ries' and Watson's *Engineering Geology*, Bowles' *The Stone Industries*.

States the principal sources are Pennsylvania, Vermont, Virginia, New York, and Maine.

In 1937, the value of building stone (exclusive of slate), produced in the United States was $146,213,128. Of this amount the limestone production totaled approximately 62 per cent, the granite 14 per cent, marble 4 per cent, trap rock 9 per cent, and sandstone 5 per cent. The value of the stone sold for various purposes was as follows: 57 per cent, principally limestone and trap rock, was marketed as crushed stone; 9 per cent was sold as rough or dressed building stone; 5.8 per cent, granite and marble, was sold for monuments; 0.5 per cent, chiefly granite and sandstone, was the value of the material sold for paving; 4.0 per cent was sold for rip-rap; 0.8 per cent, largely sandstone and granite, was sold for curbing. Nearly fifteen million dollars' worth of limestone included in the above amount was sold as flux. The production of slate in 1937 for the United States was valued at $5,605,322.

252. The Mineral Constituents of Rocks.—Inasmuch as rocks are aggregations of minerals, their properties will be dependent upon the character of these constituents. Valuable aid in determining minerals is afforded by the blowpipe and by the reactions of the minerals with acids. For identifying minerals, for ascertaining their condition, and for observing the structural arrangement in a rock, the examination of thin sections under the microscope by an expert petrographer is often of great value. Chemical analyses of rocks are of little importance except in corroborating microscopic observations. The rapid determination of mineral constitution is ordinarily made, however, through recognition of certain physical properties. The more important of these properties are hardness, cleavage, streak, color, luster, specific gravity and shape of crystals.

Hardness is probably of most importance for rapid determinations of minerals. It is measured by scratching the mineral with a series of substances of known variation in hardness, the following scale of Mohs being generally used:

1. Talc, easily scratches with the thumb-nail.
2. Gypsum, scratched by the thumb-nail.
3. Calcite, not scratched by thumb-nail, but easily cut by knife.
4. Fluorite can be cut by knife with greater difficulty than calcite.
5. Apatite can be cut only with difficulty by knife.
6. Orthoclase can be cut by knife with great difficulty on thin edges.
7. Quartz, not scratched by steel, scratches glass.
8. Topaz.
9. Sapphire.
10. Diamond.

If, for example, a given substance is scratched by calcite and not by gypsum its hardness is between 2 and 3.

Cleavage is the measure of the ease and distinctness with which a mineral may be separated on planes parallel to the crystal faces. All minerals do not exhibit cleavage and only a few possess well-marked cleavage. Easy, distinct, indistinct, perfect, and imperfect, are words often used to characterize cleavage.

Streak is the color of the mineral when in form of a powder. It is generally determined by rubbing the mineral on a bit of unglazed porcelain, called a streak stone. Since the streak of a mineral is constant in color, it is of considerable importance in distinguishing the hematites and the sulphides of metallic minerals, which vary considerably in color of mass.

Color is a valuable characteristic of the metals but is less a reliable index of the non-metallic minerals, especially if they are contaminated by coloring agents.

Luster is the surface appearance of a mineral under reflected light. It is frequently described by the following terms: Vitreous (glassy); greasy, pearly, resinous, dull, silky and metallic.

Crystal form is of importance when a mineral has had opportunity to develop its natural shape. This is not the normal condition in rock structure. Nevertheless the form is often of much importance in microscopic examinations.

In the following list will be found the most common mineral constituents of building stones together with their chemical constitution and more important physical properties.*

Quartz, silicon dioxide, is a most valuable constituent of many rocks. Hardness = 7; sp. gr. = 2.66. No cleavage. It is a colorless, white to gray sometimes brown to black mineral with a white streak and vitreous luster. It is soluble in hydrofluoric acid only and weathers well. *Flint* is a non-crystalline form of silica.

Feldspars are a group of silicates of alumina with potash (*orthoclase*) or with soda or lime (*plagioclase*). Hardness = 6; sp. gr. 2.62 to 2.75. Cleavage is good on two mutually perpendicular planes. The streak is white and the luster vitreous to pearly. Orthoclase varies in color from deep pink to whitish pink, plagioclase from gray to white. Feldspars are less durable than quartz.

Micas are silicates of alumina with hydrogen and potash (*muscovite*) or with iron, magnesia and hydrogen (*biotite*). Hardness = 2 to 3; sp. gr. = 2.7 to 3.2. Micas may be split along one plane into very thin tough plates. Their luster is vitreous to pearly and their streak is colorless or gray. In color, muscovite is colorless or gray to brown; and biotite is brown to black. Micas, especially biotite, do not weather well.

Amphibole commonly occurs as *hornblende*, a complex silicate of iron, lime, magnesia and alumina, or sometimes as *tremolite*, a silicate of lime and magnesia. Hardness = 5 to 6; sp. gr. = 2.9 to 3.5. Cleavage is perfect on two planes 124° apart but the mineral does not separate into flakes like mica. Luster is vitreous and streak uncolored, grayish or brownish. Hornblende is dark green to black, tremolite is white to gray. Hornblende weathers fairly well, tremolite poorly.

Pyroxene is chiefly found as *augite*, a silicate of lime, alumina, magnesia and iron.

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* For further information see *Engineering Geology* by Ries and Watson or *Optical Mineralogy* by N. H. and A. N. Winchell.

Hardness = 5 to 6; sp. gr. = 3.2 to 3.6. Cleavage is good on two planes 93° apart. Color is green to black. Resembles hornblende and weathers fairly well.

Olivine, a silicate of iron and magnesia, is a round-grained, greenish mineral having a hardness of 6 to 7. Its cleavage is indistinct, luster vitreous, and streak uncolored. It weathers poorly.

Chlorites are a group of aluminum silicates containing iron and magnesia. They are of greenish color and have cleavage properties like mica, but less elastic leaves. Hardness = 2 to 2.5. Streak is white to green.

Garnets are commonly silicates of iron and alumina; less often the silicates may contain lime or magnesia. Hardness = 6.5 to 7.5. Cleavage is poor, streak white, color red, and luster vitreous. They render stone difficult to dress and polish.

Serpentine is a hydrous silicate of magnesia having a greenish color and soapy feel. Hardness is usually about 4. The streak is white and luster greasy. It is soluble in hydrochloric acid and has poor resistance to weather.

Talc, another hydrous silicate of magnesia, has a hardness of 1. Splits into thin, brittle plates. Color is white to green, luster pearly. *Soapstone* is a massive form of talc.

Calcite, calcium carbonate, effervesces in dilute cold hydrochloric acid. Its color is quite variable, white when pure. Hardness = 3. Sp. gr. = 2.72. Cleavage is perfect in three directions. Slowly dissolved by waters containing traces of acids; not very durable.

Dolomite, calcium-magnesium carbonate, resembles calcite. Hardness = 3.5 to 4. Sp. gr. = 2.85. Its color is often pink and white. Effervesces in hot dilute acid but not in cold. Less soluble than calcite but not very durable.

Gypsum, hydrous calcium sulphate, is a colorless or white mineral. Its hardness is 2; sp. gr. 2.32, cleavage perfect in one plane, streak white. It is soluble in hydrochloric acid and slightly so in water.

Limonite, a hydrous sesquioxide of iron, has no cleavage. Its streak is yellowish brown. Hardness = 5 to 5.5. Sp. gr. = 3.6 to 4. Color varies from yellow to dark brown. Soluble in hydrochloric acid.

Magnetite, a combination of ferrous and ferric oxides of iron, is a black, strongly magnetic mineral. Hardness = 5.5 to 6.5; sp. gr. = 5.16 to 5.18. Cleavage is indistinct, luster metallic, and streak black. Slowly soluble in hydrochloric acid. Rusts on weathering.

Pyrite, iron disulphide, is a very common impurity in rocks. Color is brassy yellow, streak green to black, luster metallic. It has no cleavage. Hardness = 6 to 6.5; sp. gr. = 4.95 to 5.1. Oxidizes readily when exposed to the weather.

IMPORTANT STONES FOR STRUCTURAL PURPOSES

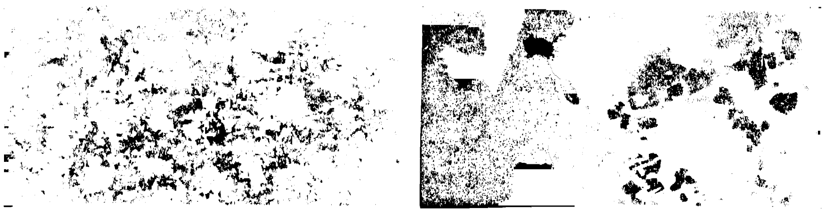
253. Classes of Rocks.—In accordance with geological origin, rocks may be classified as *igneous*, formed by the more or less rapid cooling of molten material from inside of the earth; *sedimentary*, consolidated from particles of decayed rocks which have been deposited from streams of water; and *metamorphic*, either igneous or sedimentary rocks which have undergone structural change due to pressure or heat. For structural purposes granite, gneiss, trap rock, limestone marble, sandstone, quartzite and slate are the most important rocks. Of these, granite and trap rock are igneous, limestone and sandstone are sedimentary, and gneiss, marble quartzite, and slate are metamorphic rocks.

254. Granites are hard crystalline rocks of igneous origin which have cooled before coming to the earth's surface. True granites consist chiefly of orthoclase feldspar and quartz plus small amounts of mica or hornblende. In commerce, and among quarrymen and engineers, the term granite has a broader meaning; it includes practically all of the crystalline igneous rocks such as the syenites, which consist of feldspar plus mica or hornblende; the diorites, which are mainly hornblende plus plagioclase feldspar; the coarse-grained gabbros, which are chiefly pyroxene plus feldspar; pyroxenites, which are composed essentially of pyroxene; and peridotites, which commonly consist of olivine plus pyroxene or hornblende. Although the large majority of American stone sold for granite is correctly named from the geological standpoint, we shall use the term as applied commercially herein. For most granites the chemical constitution will fall within the following limits: Silica, 65 to 75; alumina, 12 to 18; potash, 3 to 6; soda, 2 to 5; with lime, magnesia, and the oxides of iron less than 2 per cent each.

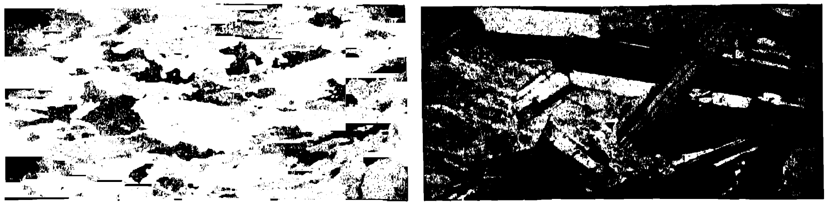
The uses to which granite may be put are largely dependent upon the size of the crystal grains, the uniformity of the structure, the color, and durability. Only those fine-grained granites, in which the crystals are a fifth of an inch or less in diameter, are suitable for work which is to be polished or carved. The medium-grained stone may be used in building construction but the very coarse-grained rocks are, in most cases, only fit for crushed stone. Photomicrographs of thin sections of granites are shown in Figs. 1*a* and 1*b*.

The uniformity of the structure of granite is often broken in several ways. *Rift* is an obscure plane, often nearly horizontal, along which the rock can be most easily split; *grain* is the plane perpendicular to the rift along which the rock splits, but with more difficulty than along the rift; and *head* or *cut-off* is the plane upon which the stone does not split. It is likely that both rift and grain were caused by strains set up in cooling from the molten state. *Joints* are fractures, produced by internal cooling strains or temperature changes, which separate the rock into sheets or beds running parallel to the surface. The above-mentioned structural imperfections generally render the stone easier to quarry; although, in some cases, where the layers are very thin or the joints are badly disintegrated, they are detrimental to its use. Segregations of minerals, which cause spots or knots, and inclusions of rock fragments, are, however, defects which may render the rock worthless for ornamental purposes.

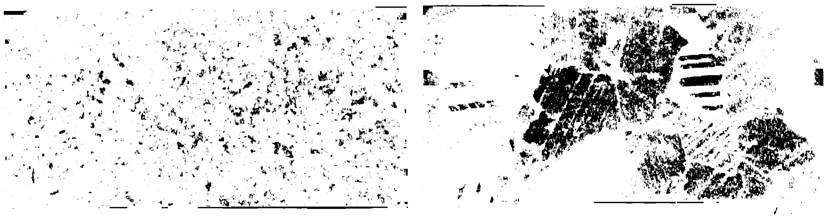
Most of the valuable granites are gray or red, although green, black and yellow stones are in use. The color of the lighter stones is largely determined by feldspar, whereas biotite, hornblende, augite, olivine and chlorite color the darker rocks. Since biotite, olivine and chlorite weather



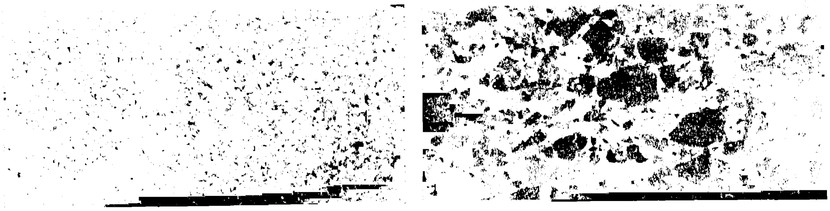
(*a*) Finely Crystalline Granite. (*b*) Coarsely Crystalline Granite.



(*c*) Hornblende Schist. (*d*) Diabase, a Variety of Trap Rock.



(*e*) Limestone. (*f*) Marble



(*g*) Very Fine Grained Sandstone. (*h*) Coarse Grained Sandstone.

FIG. 1.—Photomicrographs of Various Stones (Magnification = 14 diameters. Crossed nicols used on *a*, *b*, *d*, *e*, *f*, and *h*. Taken by L. W. Brown.)

Descriptions (Courtesy of Prof. A. N. Winchell.)—(*a*) Principally feldspar (several large crystals) and mica (feathery structure).

(*b*) Largely quartz (white) and feldspar (dark gray); strongly interlocked crystals.

(*c*) Principally hornblende (gray), feldspar and quartz (white); some magnetite (black); interlocking crystals.

(*d*) Largely augite (gray), and plagioclase (long, black and white crystals); interlocking crystals.

(*e*) Nearly all calcite; some of the grayish portions are limonite.

(*f*) Nearly all calcite crystals; not well interlocked.

(*g*) Chiefly quartz grains (white) with abundant magnetite (black).

(*h*) Mostly quartz (white), feldspar (white with fine parallel lines), biotite and magnetite (both black), lime carbonate cement.

poorly, rocks containing them are less durable than the light-colored rocks, which are likely to be free from them.

255. Gneiss.—A granite which has become laminated through metamorphism is called a gneiss. Evidently there are as many varieties of gneiss as there are granites. Many of the gneisses of the Eastern states are very hard and durable; they are much used in construction but rarely for ornamentation. Gneiss in which the foliation is very fine is called a schist, Fig. 1c.

256. Trap Rock.—Originally trap rock was the term applied to certain igneous rocks which occurred in massive layers, or in columns that presented a stepped appearance. At the present time trap rock includes the heavy dense igneous rocks which are of dark color and which, due to rapid cooling, are very fine-grained. Basalt, diabase, the fine-grained gabbros, and occasionally fine-grained diorites, are the main types of rocks so classified.

Basalt is a black, imperfectly crystallized rock which consists mainly of augite and plagioclase feldspar. It is found quite commonly in California and the Northwestern states. Diabase (Fig. 1*d*), is quite similar to basalt in mineral composition, but is more perfectly crystallized. In color it varies from green to a grayish black, the green diabases being colored by olivine or chlorite. Sheets and dikes of diabase associated with red or brown sandstone are widely found in the states along the Atlantic Coast. The chief difference between gabbro and diabase lies in the kind of pyroxene, gabbro containing a foliated form. Gabbro is found in Maryland and in Minnesota. Diorite is a dark gray or greenish rock consisting of plagioclase feldspar and hornblende sometimes with a small amount of biotite. It is found in New York, Pennsylvania and Texas.

Owing to their somber colors, toughness, and the difficulty experienced in quarrying and cutting trap rocks, little use has been made of them for building construction. When crushed they make good road metal and aggregate for concrete. In California trap rock is also considerably used for paving blocks.

257. Limestone.—It is quite probable that most of the limestone deposits of the United States were formed from the remains of corals, molluscs and other calcareous organisms when the ocean covered these portions of the earth's surface. Limestone is the trade name for all stratified rocks, which consist principally of calcite or a combination of calcium and magnesium carbonates. Limestones which contain a considerable proportion, say 15 to 40 per cent, of magnesian carbonate are called magnesian limestones; those which contain approximately equal amounts of the two carbonates are dolomites; and those which consist principally of magnesian carbonate are termed magnesites.

In the majority of limestones the content of lime plus magnesian carbonates will run over 75 per cent. When the silica ~~content~~ is high the stone grades into a sandstone; if the clay content runs high, it approaches shale. Many limestones are contaminated with some or all of the following compounds: Clay, flint, sand, iron carbonate, iron oxide, iron sulphide, gypsum, and alkali carbonates. Of these impurities, quartz veins, flint seams and pyrite inclusions are objectionable if the rock is subjected to the weather.

Generally the grain of limestone is so fine that individual crystals are not readily distinguished by the eye (see Fig. 1*e*). In color, limestones vary from white to black, although the gray and blue rocks are the most abundant. Iron compounds are responsible for the pink, red and yellow varieties, while the presence of carbonaceous material is commonly the cause of the blue, gray or black color.

In addition to the varieties already mentioned several other classes of limestone are sometimes used for building construction. Among these are the famous oölitic limestone of Indiana (Bedford stone), which is composed of minute round grains cemented together; the fossiliferous limestones of Ohio; the coquina of Florida, a soft limestone which consists of a cemented aggregation of more or less broken shells; and the travertine of Italy, the calcareous constituents of which were deposited by running streams or springs of hot water. Italian travertine was used for the interior of the Pennsylvania Terminal in New York City and the old Coliseum at Rome.

258. Marble.—When a limestone or dolomite has become crystallized through the combined influence of great heat and pressure it is called a marble. Commercially, however, the term marble is often applied to any limestone which is capable of taking a polish; for example, the non-crystalline fossiliferous marbles of Tennessee. Besides calcite and dolomite, marbles often contain impurities, such as mica, pyrite, iron oxide, quartz, tremolite and carbon. With the possible exception of carbon, any of these impurities in segregated form is likely to cause the stone to weather non-uniformly; mica and pyrite are especially bad in this regard.

Most of the more desirable marbles are finely crystalline rocks (Fig. 1*f*), of white or gray color. Many of the marbles of the New England States, New York, Georgia and Alabama are of this type. However, both in texture and color, marble is subject to considerable variation. In some stones crystals $\frac{1}{4}$ in. in diameter are in evidence; while in the ornamental but non-weathering brecciated marbles the stone body is made up of small particles of crushed rock cemented by mineral matter. The colors of marbles range from beautiful shades of pink, yellow and red to blue, brown and black. Iron compounds are generally responsible for the yellow and red shades, while carbonaceous material produces the gray, blue and black hues.

Onyx marble is another type of ornamental stone which is of some importance commercially. These translucent rocks consist of colored bands of nearly pure calcium carbonate which have been formed by the deposition of layers of colored calcareous sediments from springs and streams of cold water. California, New Mexico, Arizona, and Utah produce small quantities of onyx marbles.*

259. Sandstone.—For the most part, sandstones consist of quartz grains cemented together by silica, clay, iron oxide, or lime carbonate. Feldspar, mica and pyrites are common accessory minerals. Sandstones are of sedimentary origin and have resulted from the consolidation of sand and gravel beds which either contained the cementing substance or were impregnated with it during the process of solidification.

Inasmuch as the color, hardness, strength and durability of sandstone are due largely to the binding agency, a knowledge of the character and condition of the cement is of great importance in judging of the value of this stone. Silica forms the most enduring binder, but it is likely to render the stone hard and difficult to work. Clay in combination with silica often makes a good binder; when segregated in seams it forms planes of weakness. Also since a clay cement greedily absorbs water, it probably weakens the resistance of the stone to freezing. Iron oxide is the main coloring agent and provides good bond. Probably the poorest cement is lime carbonate which, although strong, is somewhat soluble in rain water, and consequently weathers poorly.

Sandstones with a lime carbonate cement are termed calcareous; those containing an iron oxide binder are called ferruginous; and those having a clay cement are sometimes called argillaceous sandstones. *Quartzite* is a hard, metamorphic sandstone containing a silicious cement.

The textures of sandstones vary greatly. In most of the ornamental varieties the grains are less than a fiftieth of an inch in size, whereas some of the stones used for rough work contain stone particles several inches in diameter. Figs. 1*g* and 1*h* show fine and medium-grained sandstones. Sandstones containing rounded pebbles are called *conglomerates;* those having inclusions of angular stone are *breccias.*

The yellow, red and brown sandstones are generally colored by the oxides of iron; bluish and greenish shades are often caused by pyrite or iron carbonate; clay is likely to make the stone gray.

The following varieties of sandstone are of chief importance in building construction in the United States: Brownstone, a sandstone of granitic origin containing more or less feldspar and mica which is found in the Connecticut River Valley and in the Middle Atlantic States; Medina red sandstone of New York; Potsdam sandstone, a hard, red to brown rock quarried extensively in New York and to some extent in Northern

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* True onyx is a translucent silicious rock of wavy banded structure.

Wisconsin; and Berea sandstone, a finely crystalline stone of uniform texture and light yellow-gray color found in Ohio. Bluestone, a thinly bedded argillaceous sandstone found in New York and Pennsylvania, makes hard, tough flagstone. Gray Medina sandstone from New York, the Kettle River sandstone from Minnesota and the Ablemans sandstone from Wisconsin are used for paving blocks.

260. Slate.—When a clayey shale has been consolidated by great pressure to form a rock which may be cleaved into thin sheets, the name slate is applied. A few slates, also, have originated from the metamorphism of igneous rocks. From the compilation of a large number of analyses by Eckel * it appears that most slates contain from 55 to 70 per cent of silica, 9 to 25 per cent of alumina, with small percentages of iron oxide, lime, magnesia, and the alkalies. The presence of iron sulphide is undesirable, since in weathering it is likely to produce rust discolorations on the surface of the slate. Slates exhibit a wide range in color from green to black. The green varieties commonly owe their color to the presence of chlorite. Most of the non-fading slates are gray or black in color.

About three-fourths of the slate produced in this country is made into roofing and the majority of the remainder is used for structural and electrical purposes, blackboards, and grave vaults.

THE DURABILITY OF STONE

261. The Weathering of Structural Stone.—This term includes the resistance of stones, when exposed to the weather, to all the disintegrating actions of heat and cold, water, frost, and chemical action, which combine in this climate to effect the rapid decomposition and destruction of most of the rocks, and of many of those which have been selected for building purposes. A stone building or monument should remain in good preservation for hundreds of years, but more commonly they begin to scale and crumble before they are twenty-five years old. The life of a rock may be many thousands of years in Egypt, or Italy, or Greece, when it would not last as many scores of years in the United States.

In quarrying and cutting the stone certain conditions arise which affect its weathering properties. Stone from the top ledges of limestone, granite and slate and from the exposed faces of the rock bed is likely to be less hard and durable than material unexposed to ground water and the weather. The method of blasting and cutting also influences the strength of the stone and its resistance to freezing and temperature changes. Small charges of powder uniformly distributed have a lesser weakening effect than large concentrations of explosives. Repeated hammering in cutting is also likely to injure the stone. Some claim saw-cut stone is more durable than that finished by the hammer. Doubtless polished stone is more enduring than rough surfaced work, since the rain slides off the former more easily. Quarrying of highly absorbent stone, like the more porous sandstones, in freezing weather is bad practice, since the rock is full of quarry water and is likely to be split by freezing action. Although most stones work more readily when freshly cut and full of quarry water, yet it is unwise to lay stone in a wall immediately after quarrying. Such procedure hinders evaporation of the water and thereby lessens the strength of the stone.* In laying stratified rock, like argillaceous sandstones, brownstones or gneisses, the natural beds should be placed horizontal in order to secure maximum weathering resistance.

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* *Building Stones and Clays*, p. 97.

Probably the most important disintegrating agent in the case of relatively impervious rocks is the variation of temperature. If one considers that most of the rocks are composed of minerals, each of which may have a different coefficient of expansion and that the crystals of a given mineral have different coefficients along their different axes, it will be appreciated that the unequal temperatures in various parts of a stone due to the way it is exposed must produce large stresses and deformations within it. Furthermore, experiments have shown that there is always some set after the temperature has been reduced (see Art. 267). Consequently, the alternate expansion and contraction due to unequal heating by the sun slowly but surely break down the structure of the stone.

The porosity of the stone and the character of its pores affect its resistance to freezing. A porous stone is less resistant to freezing than a dense stone of like pore structure and composition. It is probable that a porous stone having large pores and small tubes connecting the pores is weakened more by freezing than a stone having large pores and large connecting tubes. Also rocks with tortuous pores and tubes are more apt to be injured by freezing than those of equal porosity having straight pores and tubes.

Pyrite, magnetite, and iron carbonate oxidize in weathering and cause discoloration of the stone in which they are present. Since this oxidation is accompanied by a change in volume, the surrounding structure is weakened. When, however, pyrite is very finely and uniformly distributed through the stone, as in Berea sandstone, the structural injury due to oxidation seems to be negligible. Pyrite inclusions in limestone, or in a calcareous sandstone, are very objectionable since they may form sulphuric acid during the weathering process and the latter attacks the lime and magnesia compounds.

Inasmuch as the atmospheric water and rain of most large cities contain appreciable quantities of acid, mainly carbonic and sulphuric, the solubility of the carbonates, and to a lesser extent biotite, plagioclase feldspars, and hornblende, should be remembered when selecting building stones for such localities. Limestones, marbles, the laminated micaceous brownstones, and calcareous sandstones are the greatest sufferers from the solvent action of acidulated water.

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* It is claimed that the evaporation of the quarry water leaves the mineral matter which it contains in the pores of the rock, thus producing a denser and stronger surface on the stone.

The following table prepared by Dr. A. A. Julien shows the estimated life of various building stones when exposed to weather in New York City.*

Kind of Stone.	Life in Years
Coarse brownstone	5 to 15
Fine laminated brownstone	20 to 50
Compact brownstone	100 to 200
Bluestone (sandstone), untried, probably centuries.	
Nova Scotia sandstone, untried, perhaps	50 to 200
Ohio sandstone (best silicious variety), perhaps from one to many centuries.	
Coarse fossiliferous limestone	20 to 40
Fine oölitic (French) limestone	30 to 40
Marble, coarse dolomitic	40
Marble, fine dolomitic	60 to 80
Marble, fine	50 to 100
Granite	75 to 200
Gneiss, 50 years to many centuries.	

Efflorescence on limestone can often be removed by a blast of steam at 125 lb./in.^{2} pressure, followed by an immediate washing with a 5 per cent solution of formic acid.†

262. Preservative Coatings for Stone Work.—Among the more valuable preservative treatments applied to deteriorating stone work are boiled linseed oil, paraffine, and paraffine or wax in volatile solvents. Before application the stone work must be clean and dry. Under severe exposures treatment renewals will be occasionally required.

Boiled linseed oil is brushed on in two or three coats and followed by a coat of dilute ammonia in warm water. The latter application unifies the discoloration produced by the oil.

Melted paraffine is sometimes applied by a brush and then forced into the pores of the stone by heating the surface to a temperature of about 60° C. In treating the surface of the Egyptian obelisk in New York City, the paraffine contained a solution of creosote and naphtha. The purpose of the creosote was to prevent organic growth on the stone.

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* Report Tenth Census, 1880, Vol. 10, p. 391.

† See *Bulletin* No. 33, Purdue University; also *Proc. A.S.T.M.*, Vol. 28, Pt. 2, p. 695.

For stone of medium or coarse texture, D. W. Kessler (see U. S. Bur. Standards *RP771*) states that paraffine with a melting temperature above 60° C., dissolved in proportion of 6 to 12 oz. to a gallon of naphtha, makes an effective and durable treatment when sprayed or brushed on the work. For fine pored stone the addition of 3 to 6 oz. of china oil increases ease of penetration, but may cause an oily discoloration.

263. The Value of Durability Tests.—By far the best, and perhaps the only infallible, test of the weathering qualities of any given stone is the examination of a ledge of it which has been long exposed, or of an old building, slab, or monument made from the same ledge in the quarry. Inasmuch as this test cannot be applied to a new quarry without an exposed face, and because durability is by far the most important property of any building stone, the following artificial tests are sometimes used to determine durability: freezing and thawing tests, acid tests, and fire tests.

264. Freezing and Thawing Tests.—A satisfactory procedure consists in preparing 10 representative 2-in. cubes and subjecting 5 to freezing and thawing. Before freezing and thawing the cubes are weighed and immersed for 24 hr. in clean water; then they are placed in a freezer at 10 to 20° C. The test is more drastic if the specimens are frozen immersed in water. After they are thawed for 1 hr. in circulated water at 20 to 25° C., the cycle is repeated. After intervals of 25 cycles, losses in weight are determined, and, whenever an appreciable effect has been produced, all cubes are crushed in wet condition. The number of cycles withstood prior to marked disintegration and the ratio of strength frozen to normal afford indices of durability. Kessler in *Tech. Paper* 349, U. S. Bur. Std., reported that 25 out of 65 types of native limestones withstood more than 1000 cycles of freezing (in air) and thawing before exhibiting marked disintegration.

The resistance of crushed stone can be estimated by finding the reduction in particle size after 100 or more cycles of freezing and thawing.

From a large number of tests on 2-in. cubes of Wisconsin stones in which thirty-five repetitions of freezing were used, Buckley found that granites and rhyolites * lost less than 0.03 per cent, limestones less than 0.30 per cent and sandstones less than 0.62 per cent by weight. In crushing tests, frozen samples showed less strength than normal specimens, some of the frozen specimens exhibiting less than 50 per cent of the strength of equally perfect normal test-pieces. Other results gotten by Bauschinger on the effect of freezing on crushing strength appear in Table 6.

Tests by Hirschwald † show that the resistance to freezing is dependent on the percentage of pore space occupied by water. In experiments on a number of different rocks he showed that a comparatively small number of freezings would rupture rocks which were saturated with water under pressure, whereas 25 to 30 freezings affected but little those which were immersed at atmospheric temperature and pressure. Consequently, in making the freezing test, conditions surrounding the soaking of the specimens should be uniform and the aim should be to fill the pores as much as they ever would be filled in service.

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* A dense, fine-grained igneous rock with occasional large crystals of quartz or feldspar which has cooled near the surface of the earth and which has much the same mineral constitution as true granite; often termed quartz porphyry.

† Reported in *Handbuch der Bautenischen Gesteinsprüfung*, Hirschwald; also *Engineering Geology*, Ries and Watson.

Owing to the length of time and cost of freezing tests, accelerated soundness tests, based on the expansive action of crystallizing salt, such as sodium or magnesium sulphate, are often used. Essentially the sodium sulphate test * consists of 5 or 10 cycles of the following procedure: submerge a 5000-gram sample of crushed rock sized in a standard manner in a saturated solution of sodium sulphate maintained at 21° C. for 18 hr., dry at 105 to 110° C. for 4 hr., then cool in air for 2 hr. The losses in weight retained on the standard sieves serve as an index of damage, but failure in the test should not be considered conclusive evidence of unfitness of a stone.

265. Acid Tests.—To ascertain the resistance of stone to acidulated waters and the acid atmosphere common to the large cities, tests have been made to determine the disintegrating effect of sulphurous and carbonic acid gases upon samples of stone. In making such tests carefully prepared cubes of equal size are dried to constant weight at 110° C. They are then placed in a large jar provided with a humidifier of some sort, and so made that it may be hermetically sealed. A stream of washed gas is then pumped through the jar until all air is expelled. The jar is then sealed for two or three days when another application of gas is administered. At the conclusion of a couple of months the test is discontinued, and the specimens are examined and weighed.

In tests on $\frac{3}{4}$-in. cubes of a number of stones, chiefly from New York, Wilber † found the maximum percentage losses in weight shown in Table 1.

In 44-day tests on eleven limestones of Wisconsin, Buckley found a maximum loss in weight of 1.13 per cent in sulphurous acid gas and 0.11 per cent in carbonic acid gas. His 1-in. and $1\frac{1}{2}$-in. cubes were badly discolored and some showed magnesium incrustations on the surface. Outside of the weight lost the effect of the carbonic acid gas was not perceptible.

Slate is sometimes tested for resistance to acidulated waters by immersing small fragments in a very dilute mixture of hydrochloric and sulphuric acids and noting the losses in weight. Merriman ‡ in his tests used 1 part

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* See Test for Soundness of Coarse Aggregates, *A.S.T.M. Tent. Std.*

† *Bulletin* 10, N. Y. State Museum, p. 357; also see *Building Stones and Clays* by E. C. Eckel, p. 209. (Out of print.)

‡ *Bulletin* 275, U. S. Geol. Survey.

TABLE 1.—THE EFFECT OF ACID ATMOSPHERES UPON DIFFERENT STONES. (WILBER)

Kind of Stone	No. of Tests	Maximum Per Cent Loss in Weight when Immersed in	
		CO_2*	HS_2†
Granite	4	.029	024
Marble	4	.017	.250
Limestone	13	.087	.250
Sandstone	30	.104	.250
Slate	1	.004	.070

* Tested 52 days. † Tested 31 days.

hydrochloric, 1 part sulphuric acid and 98 parts of water. He immersed 3×4-in. specimens in this solution and determined the dry weight before and after a 63-day immersion period. The average loss in weight of the varieties which he tested ranged from 0.286 to 0.768 grain; all but one variety had less than 0.4 grain loss.

It should be always borne in mind when making tests or comparing weight losses in corrosion tests that a knowledge of the segregated intensity of the action of the acid is often of more importance than the total loss in weight.

266. Fire Tests.—During conflagrations stone buildings often suffer severely. Under such conditions stone must be classed as inferior to structural clay or Portland cement products. The comparatively low resistance of building stone to high temperatures is undoubtedly due to a combination of stresses set up by the great differences in the coefficients of expansion of the constituent minerals, and also to the low heat conductivity of the rock. Quenching with a fire hose accentuates the stressed condition and often badly cracks the stone or causes thin slabs to spall off.

The relative resistances of different stones to high temperatures may be compared and the effect of structural and mineralogical differences observed by placing cubes in a muffle furnace and subjecting them to temperatures ranging from 500° to 900° C. The temperatures should be read by pyrometers so placed that the temperature of the specimens and not the flame is determined. In this connection it is well to have one or two specimens bored to take a thermo-couple, so that the inside temperature of the specimens may be estimated. When testing cubes 4 in. or less in diameter, the temperature should be held constant for at least one-half hour. The effect of variations in temperature on the strength of stone is a subject deserving of study.

For determining the resistance of stone work to fire, the only satisfactory method of testing is to build a small hut or a wall panel of stone and mortar and subject one side of the structure to high temperature, 1700° F. after 1 hr. to 2300° F. after 8 hr. are the furnace temperatures specified in A.S.T.M. Standards (see Art. 543).

From a considerable number of tests on small cubes reported by W. E. McCourt (*Bull.* No. 100, N. Y. State Museum), and others by E. R. Buckley (*Bull.* No. 4, Wisconsin Geol. and Nat. Hist. Survey), the following conclusions seem justifiable:

None of the common building stones, granite, gneiss, limestone, marble, or sandstone, will withstand temperatures above 850° C. Coarsely grained granite, gneiss, porous sandstones and the coarsely crystallized marbles begin to show signs of disintegration at temperatures as low as 550° C. Limestone and marble withstand heating as well as any of the igneous rocks until the temperature is reached at which calcination begins (600 to 800° C.); then they rapidly disintegrate. Fine-grained, dense sandstone with silicious cement is very resistant to fire, but the good aspect of badly disintegrated cubes which had been heated to 850° C. indicates that the appearance of this material after a fire is misleading. Fine-grained granite at 850° C. exhibits more or less cracks but is not badly disintegrated.

Fire tests of panels of stone which were laid with broken joints in cement mortar and backed with brick or tile are reported in *Bulletin* No. 370 of the U. S. Geol. Survey. The tests were made as indicated in Art. 543. Granite, sandstone, limestone and marble panels were tested, the stone for these panels being bought in the Chicago market. The stones composing the panels were $4 \times 7\frac{3}{4}$ in. in cross-section. Part were laid with the narrow edge and part with the wide edge exposed. After being subjected to a temperature of 900° to 1000° C. for one hour and then soaked with a fire hose, none of the panels were in good condition. The majority of the stones in each panel were badly cracked and in some cases the faces were spalled to the depth of 2 or 3 in. No satisfactory comparison of the resistance of different classes of stone can be made on the basis of these tests.

THE PHYSICAL PROPERTIES OF STONES

267. The Thermal Expansion of Stone.—Aside from its effect in weathering of stone, Art. 261, thermal expansion has a marked effect on stresses set up in stone when restrained and subjected to temperature changes. Usually stones show variations in their coefficients in different ranges of temperature; coefficients for limestones are less at room temperatures, or slightly below, than at 100° C. Most stones exhibit permanent expansion after heating to the boiling point of water: thus in Tests of Metals, 1895, bars of granite, sandstone, limestone, and marble heated in water exhibited permanent average unit expansions of 0.00019, 0.00026, and 0.00037, respectively. Apparently, from a few tests conducted with copper-jacketed bars, a third of this expansion was due to entrance of water into the stones.

The maximum, average, and minimum values from the accurate tests made by J. H. Griffth, and reported in *Bull.* 128 and 131 of the Iowa Engineering Experiment Station, have been summarized in Table 2. In Griffth's tests the bars were heated in an electric furnace, without immersion in water. His data show that for rocks containing silica the thermal expansion increased with the proportion of free silica. Rocks having the most free silica expanded most, whereas those having the most combined silica expanded least.

TABLE 2.—PHYSICAL PROPERTIES OF AMERICAN ROCKS (Griffith)

Maximum, mean (in bold face type), and minimum observed values are recorded

Kinds of Stone	No. of Kinds	Shore Hardness Number	Coef. of Thermal Expansion $\times 10^{-7}$ per °F.	True Specific Gravity	Weight in lb./ft.^{3}	PERCENTAGE		Crushing Strength, lb./in.^{2}
						Absorption by Weight	Porosity by Weight	
Rhyolite-Granite	22	104 **89** 51	66 **44** 19	3.04 **2.66** 2.59	187 **163** 155	1.7 **0.6** 0.2	4.1 **1.5** 0.4	42,500 **23,100** 8,830
Andesite-Diorite	5	93 **78** 66	57 **36** 23	3.02 **2.75** 2.49	185 **177** 139	4.9 **1.2** 0.0	10.8 **2.8** 0.1	32,700 **24,490** 13,610
Basalt-Gabbro	11	96 **79** 54	50 **31** 20	3.00 **2.83** 2.70	184 **172** 138	10.0 **1.1** 0.0	22.0 **2.6** 0.0	38,000 **23,260** 6,540
Sandstone	8	86 **57** 22	65 **54** 37	2.66 **2.61** 2.52	161 **146** 133	13.8 **4.8** 0.7	26.4 **10.4** 1.6	33,350 **15,940** 4,920
Limestone-Dolomite	18	96 **54** 28	68 **42** 17	2.80 **2.71** 2.65	170 **166** 143	6.0 **0.9** 0.1	13.7 **2.1** 0.2	26,900 **16,270** 8,470
Gneiss	5	99 **87** 71	44 **35** 13	3.15 **2.77** 2.62	195 **171** 163	0.8 **0.4** 0.1	2.2 **1.0** 0.3	29,400 **20,030** 12,950
Quartzite	3	97 **90** 78	61 **60** 60	2.68 **2.65** 2.63	167 **165** 163	0.3 **0.2** 0.1	0.6 **0.5** 0.3	43,800 **33,680** 23,440
Slate	4	75 **55** 30	49 **44** 35	2.88 **2.80** 2.76	174 **172** 169	1.3 **0.5** 0.0	3.6 **1.4** 0.0	19,100 **18,370** 17,770
Marble	8	66 **48** 38	51 **45** 38	2.88 **2.68** 2.50	179 **166** 156	0.8 **0.3** 0.1	2.0 **0.7** 0.3	32,450 **20,070** 13,180

268. Specific Gravity and Specific Weight.—The specific gravity is an important property for two reasons: The higher the specific gravity the greater the stability of an hydraulic structure built of the stone; also for a given kind of stone the strength increases with the specific gravity or density. The superiority of heavy stone for dam or retaining wall construction is apparent if one computes the ratio of the weights of a light and a heavy stone when submerged in water.

There are three ways of determining the specific gravity of substances like stone, all of which are in use to some extent. In the first method, used by Griffith, the dried stone is pulverized and the specific gravity is found by the method used in testing cement (Art. 409); this method if properly applied gives the true specific gravity of the stone substance. The second method consists in drying the stone to constant weight, coating it with a thin film of paraffine, and then determining the weight of the stone immersed in water. The loss in weight divided into the dry weight gives the bulk specific gravity (i.e., the specific gravity of the stone, including its pores). The third method differs from the second in that the dried stone is saturated (?) with water and then weighed under water. Since it is impossible to fill completely the pores of the stone, the third method gives results intermediate between those of the first and third methods. If the specific weight is computed by multiplying the specific gravity by 62.4, the results from the second method are of most importance to engineers. Values of specific gravity and specific weight appear in Tables 2 to 5.

269. Porosity and Density.—The porosity of a stone is the ratio of the volume of its pores to the entire volume of stone plus pores. Density $=1-$porosity. Porosity may be accurately computed as follows: The stone, dried to constant weight, is coated with paraffine and weighed suspended in water. The loss in weight in water divided by the weight of a cubic unit of water gives the volume of stone plus pores. The volume of the stone substance may be gotten by dividing the dry weight of the stone by the product of the specific gravity of its powder and the weight of a cubic unit of water. The porosity or the density is then readily computed. Griffith's values for porosity are given in Table 2.

In tests on a large number of Wisconsin and Missouri stones E. R. Buckley found the following ranges in porosity for the different classes of rock: Granites, 0.019 to 1.45; limestones, 0.32 to 13.38, and sandstones, 4.81 to 28.28 per cent.* In calculating the pore space Buckley determined the volume of water absorbed by the stone under vacuum at a temperature of 100° C.

The per cent porosity in conjunction with the per cent absorption is of value in judging of the resistance of porous materials to freezing.

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* See *Bull.* 4, Wisconsin Geol. and Nat. Hist. Survey, p. 400; and *Bull.* 2, Mo. Bureau Geol. and Mines, 2d series, p. 317.

TABLE 3.—PHYSICAL PROPERTIES OF BUILDING STONES

Condensed from Merrill's *Stones for Building and Decoration*

Kind of Stone.	Locality.	Position.	Strength per Square Inch.	Specific Gravity.	Weight per Cubic Foot.	Percentage of Absorption by Weight.	Number of Specimens averaged.
			Lb.		Lb.		
1. Granite	Grape Creek, Brownsville, Lawson, Platte Cañon, Cotopaxi, Monarch, Gunnison—*Colo.*	Bed Edge	15,531 18,536	2.68	167.0	1.1	8
2. Granite	New London, Millstone Point, Mystic River, Stony Creek—*Conn.* Vinalhaven, Fox Island, Dyer's Island, City Point, Dix Island, Jonesboro, Sprucehead, Hewitt's Island, Hurricane Island—*Maine.* Huron Island—*Mich.*	Bed	16,200	2.65	166.0	0.4	20
3. Granite	East Saint Cloud, Saint Cloud, Watab, Sauk Rapids, Beaver Bay—*Minn.*	Bed Edge	24,464 24,464	2.65	165.8	0.5	7
4. Granite	Cape Ann, Rockport, Quincy—*Mass.*	Bed	16,079	2.67	167.0	0.7	4
5. Granite	Fall River, Monson — *Mass.* Keene — *N. H.* Tarrytown, Morrisania, Staten Island, North River, Madison Avenue, Chaumont Bay—*N. Y.* Westerly — *R. I.* Richmond —*Va.*	Bed	15,570	2.69	168.0	0.4	14
6. Granite	New Haven — *Conn.* Duluth, Taylor's Falls, Beaver Bay—*Minn.* Jersey City Heights, Pompton—*N. J.* Goose Creek (Loudoun County)—*Va.*	Bed Edge	21,272 20,740	2.82	176.2	0.3	6
7. Limestone (oölitic)	Putnamville, Greensburgh, Saint Paul, Harrison County, Mount Vernon, Bloomington—*Ind.*	Bed	14,054	....	156.2	1.4	6
8. Limestone	Spencer, Ellettsville, Bedford, Salem—*Ind.*	Bed	9,297	....	145.9	3.6	8
9. Limestone	Bardstown—*Ky.*	Bed Edge	16,250 15,000	2.67	166.9	1.2	1
10. Limestone	Lee—*Mass.*	Bed Edge	22,323 21,728	....	......	....	3
11. Limestone	Frontenac, Stillwater, Winona Red Wing, Kasota, Mantorville—*Minn.*	Bed Edge	16,320 16,643	2.52	157.3	3.1	7
12. Limestone	Glens Falls, Lake Champlain, Canajoharie, Kingston, Garrison's Station, Williamsville—*N. Y.*	Bed Edge	16,971 15,533	2.58	168.1	....	6

PHYSICAL PROPERTIES OF BUILDING STONES—*Continued*

Kind of Stone.	Locality.	Position.	Strength per Square Inch.	Specific Gravity.	Weight per Cubic Foot.	Percentage of Absorption by Weight.	Number of Specimens averaged.
			Lb.		Lb.		
13. Limestone (marble)	Montgomery County—*Pa.*	Bed Edge	13,112 11,055	....	......	....	4
14. Limestone (marble)	Dorset—*Vermont.*	Bed Edge	10,506 8,670	2.64 2.68	164.7 167.8	....	2 1
15. Limestone (marble)	Italy.	Bed	12,156	2.6.	168.2	....	1
16. Sandstone	Buckhorn (Larimer Co.), Trinidad (Las Animas Co.), Manitou (El Paso Co.), Ralston, Left Hand, Saint Vairus, Fort Collins (Larimer Co.), Stout (Larimer Co.)—*Colo.* Thistle—*Utah.*	Bed Edge	11,141 12,434	2.13	132.9	6.6	9
17. Sandstone	Coal Creek, Oak Creek (Fremont Co.), Gunnison (Gunnison Co.), Manitou (El Paso Co.), La Porte (Larimer Co.), Brandford (Fremont Co.)—*Colo.*	Bed Edge	5,481 4,941	2.12	133.0	13.8	9
18. Sandstone	Middletown, Portland—*Conn.* East Long Meadow—*Mass.* Marquette—*Mich.*	Bed	6,639	2.27	142.2	3.5	3
19. Sandstone	Hinckley, Fort Snelling—*Minn.*	Bed Edge	16,625 18,750	2.23	139.0	6.0	2
20. Sandstone	Dresbach, Jordan, Fond du Lac, Dakota—*Minn.*	Bed Edge	5,789 4,102	1.99	124.4	9.9	6
21. Sandstone	Taylor's Falls, Kasota, Frontenac—*Minn.*	Bed Edge	7,483 9,725	2.28	142.3	5.9	3
22. Sandstone	Haverstraw, Hudson River, Albion—*N. Y.*	Bed Edge	8,925 7,687	2.28	142.2	2.6	2
23. Sandstone	Medina—*N. Y.*	Bed Edge	17,500 14,812	2.42 2.39	150.8 149.3	1.6 2.0	2 1
24. Sandstone	Vermilion—*Ohio*	Bed Edge	7,840 6,875	2.16	135.0	5.2	5 1
25. Sandstone	Seneca—*Ohio.*	Bed Edge	9,687 10,500	2.39	149.3	3.1	1
26. Sandstone	Cleveland—*Ohio.*	Bed Edge	6,800 7,910	2.24	140.0	2.8	1
27. Sandstone	Marblehead—*Ohio.*	Bed Edge	7,937 6,850	2.31	144.4	5.2	1
28. Sandstone	North Amherst—*Ohio.*	Bed Edge	6,212 5,450	2.16	133.7 135.8	5.2	2 1
29. Sandstone	Berea—*Ohio*	Bed	9,236	2.13	133.0	5.5	2

270. Absorption.—Methods for testing the absorption of stone differ. After drying 5 or more samples for 24 hr. at 110 to 120° C. and cooling before weighing, the absorption can be found after submersion in distilled water for 14 days, or after boiling 5 hr. (see Art. 291).

The proportion of the pore space filled with water and the rate at which the rock will expel absorbed water are important criteria of resistance to freezing. Rocks which absorb enough water to fill the pores and which expel slowly are very likely to be weakened by freezing.

Values of the percentage of absorption for different stones may be found in Tables 3 and 4. Griffith soaked his specimens overnight, boiled them 3 hr., and cooled them in water several hours before determining absorption.

THE MECHANICAL PROPERTIES OF STONE

271. The Strength of Stone.—The compressive strength of building stone is the most commonly tested mechanical property; although shearing, and transverse tests are sometimes made.

For rock which is to be used in road construction toughness and resistance to abrasion are common determinations (see Art. 273 and Standard Specifications of A.A.S.H.O.). The preparation of specimens and methods of making compression tests are considered in Ch. III. Considerable uncertainty exists concerning methods of preparing and bedding used in obtaining the older data reported herein, but in Griffth's tests the bed planes were ground and no capping was used. He found the difference between tests run parallel and normal to the rift was only 5 to 10 per cent.

From a study of the relation of the percentage of absorption, A, by weight to the ultimate crushing strength, S_c, in pounds per square inch, Griffith concluded that practically all the reliable test averages fell within the zone $S_c(A+4) = 80{,}000\ (1 \pm \frac{1}{4})$.

Although a high crushing strength is important where a heavy load is to be borne by a single stone, other properties may be more desirable in masonry constructions where the maximum stresses are commonly less than 800 lb. per sq. in. Crushing strengths of the more important stones of the United States are given in Tables 2, 3, and 4.

Owing to faulty methods of quarrying, discrepancies between the rift and planes of bedment in the wall, and owing to irregularities in foundations and mortar bedments stone is much more likely to crack because of the imposition of bending stresses than by crushing. Cracks in lintels due to transverse stresses and in walls due to excessive shear stresses are quite common. Consequently, the resistance of stone to these stresses is of importance.

TABLE 4.—TESTS OF AMERICAN BUILDING STONE MADE AT THE WATERTOWN ARSENAL

(Rep. 1894.)

Name of Stone.	Weight per Cubic Foot.	Compression Tests.		Ratio of Lateral Expansion to Longitudinal Compression.*	Shearing Strength.	Coefficient of Expansion in Water per °F.
		Strength in Pounds per Square Inch.	Modulus of Elasticity for Working Loads.			
	Lb.		Lb./In.^{2}		Lb.	
Brandford granite (Conn.)...	162.0	15,707	8,333,300	0.250	1833	.00000398
Milford granite (Mass.).....	162.5	23,775	6,663,000	0.172	2554	.00000418
Milford granite (Mass.).....	.....	....	....	....	....	.00000415
Troy granite (N. H.)........	164.7	26,174	4,545,400	0.196	2214	00000337
Milford pink granite (Mass.)	161.9	18,988	5,128,000	....	1825	
Pigeon Hill granite (Mass.)..	161.5	19,670	6,666,700	....	1550	
Creole marble (Georgia).....	170.0	13,466	6,896,500	0.345	1369	
Cherokee marble (Georgia)..	167.8	12,618	9,090,900	0.270	1237	.00000441
Etowah marble (Georgia)....	169.8	14,052	7,843,100	0.278	1411	
Kennesaw marble (Georgia)..	168.1	9,562	7,547,100	0.256	1242	
Lee marble (Mass.).........	.....	....	....	....	....	.00000454
Marble Hill marble (Ga.)...	168.6	11,505	9,090,900	0.294	1332	.00000194
Tuckahoe marble (N. Y.)....	178.0	16,203	13,563,200	0.222	1490	.00000441
Mt. Vernon limestone (Ky.).	139.1	7,647	3,200,200	0.250	1705	.00000464
Bedford blue limestone (O.)	.....	10,823	7,250,000	0.270	1017	.00000389
North River bluestone (N. Y.)	.....	22,947	5,268,800			
Monson slate (Maine).......	.....	....	....	....	....	.00000519
Cooper sandstone (Oregon)..	159.8	15,163	2,816,900	0.091	1831	.00000177
Sandstone, Cromwell (Conn.)	.....	10,780				
Maynard sandstone (Mass.).	133.5	9,880	1,941,700	0.333	1204	.00000567
Kibbe sandstone (Mass.).....	133.4	10,363	1,834,900	0.300	1150	.00000577
Worcester sandstone (Mass.).	136.6	9,762	2,439,000	0.227	1242	00000517
Potomac sandstone (Md.)...	.....	....	....	....	....	.00000500
Olympia sandstone (Oregon).	.....	12,665	....	....	....	.00000320
Chuckanut sandstone(Wash.)	.....	11,389	....	....	1352	
Dyckerhoff Portland cement, neat..................	....	....	....	....	....	.00000578

* Poisson's ratio.

In Table 4 are given the shearing strengths for a number of American stones. Inasmuch as the majority of these tests were made by a method similar to that outlined in Art. 514 (Fig. 15, Ch. XIV), the values are probably lower than the true shearing strength due to bending. While testing the transverse strength of Wisconsin stones, Buckley found the following ranges in modulus of rupture: Granite, 2713 to 3910; limestone, 1164 to 4659, and standstone, 363 to 1324 lb. per square inch. In Table 6 is presented a series of tests on Bavarian building stones. These tests were made with great care and precision by Prof. Bauschinger and reported in his *Communications*, Vol. 10. The results show that there is no fixed relation between the various kinds of strength of stone.

A considerable number of transverse tests were made by Prof. Merri-

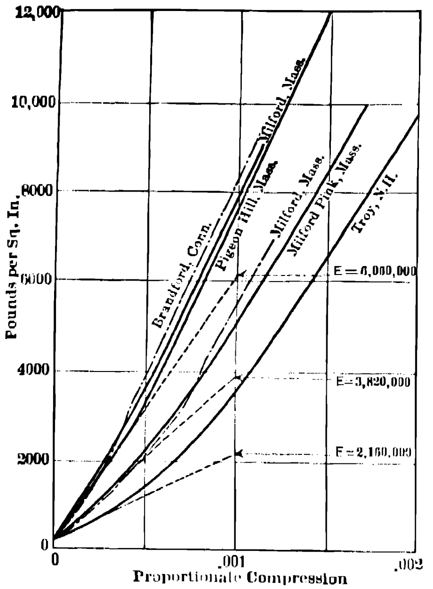

FIG. 2.—The Elastic Properties of Various Granites under Compressive Stress. (*Wat. Ars. Rept.*, 1894.)

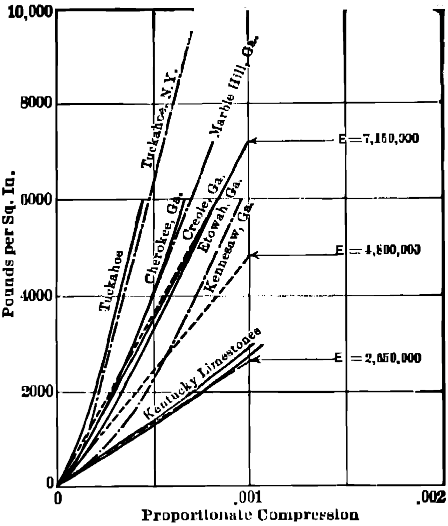

FIG. 3.—The Elastic Properties of Various Limestones and Marbles under Compressive Stress. (*Wat. Ars. Rept.*, 1894.)

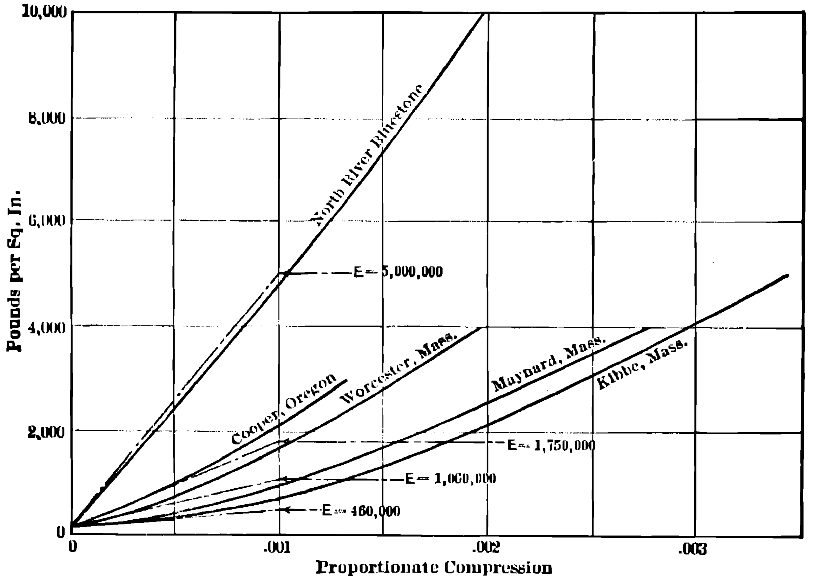

FIG. 4.—The Elastic Properties of Various Sandstones under Compressive Stress. (*Tests of Metals*, 1894.)

man * on slate specimens which were secured from a number of the Eastern states. The specimens were 24×12 in. in plan and $\frac{3}{16}$ to $\frac{1}{4}$ in. thick. They were tested flatwise on a 22-in. span. The values of the average modulus of rupture for nine varieties ranged from 6410 to 9880 lb. per square inch, and the average maximum deflection varied from 0.19 to 0.23 in. It seems reasonable, therefore, to expect good slate to have a modulus of rupture of 7000 lb. per square inch and to deflect 0.20 in. at rupture.

Experiments made at the Watertown Arsenal † have shown that a very great loss in tranverse strength results from immersing stone in hot and cold water. The granites were the least affected and the marbles most. The loss in strength of the former, for the most part, was less than 25 per cent while several of the marbles lost 50 per cent of their strength due to this treatment. Consequently, one must be careful that specimens of stone for transverse tests are not subjected to large temperature variations. Furthermore, this fact should be borne in mind in designing lintels and stone beams which will be subjected to wide variations of temperature.

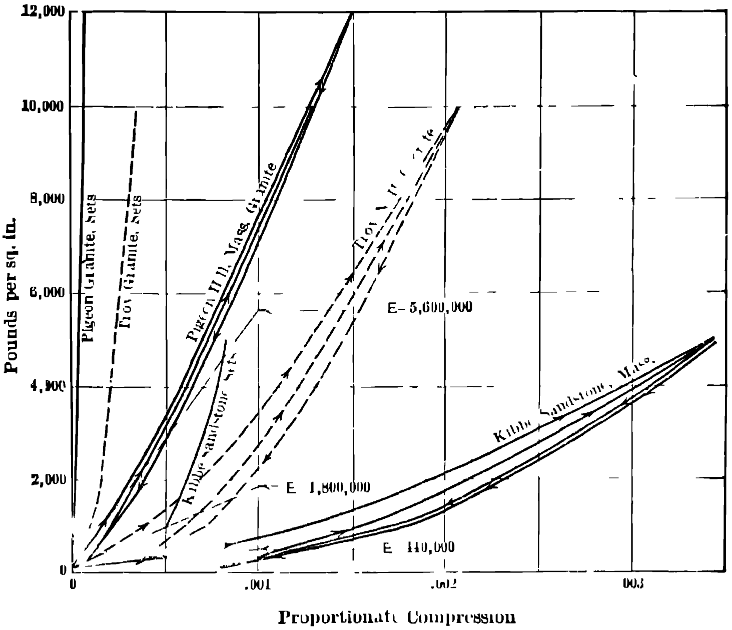

FIG. 5.- Elastic Properties of Various Stones under Compressive Stress (*Tests of Metals*, 1894.)

272. The Elastic Properties of Stone. Like cast iron, brick and concrete, stone is a material which does not obey Hooke's law. The granites, limestones and marbles, however, exhibit less curvature and less set in their stress-deformation curves than do the more porous sandstones. These facts will be evident after an examination of Figs. 2, 3, 4 and 5. Bauschinger has shown, however, that for a given specimen the moduli of elasticity in tension, compression and in cross-bending are practically the same. The values which are taken from his tests, Table 5, were found on the first loading.

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* *Bull* No 275, U. S. Geol. Survey.

† *Tests of Metals*, 1905.

TABLE 5.—PROPERTIES OF THE BUILDING STONES OF BAVARIA
(Bauschinger's *Communications*, Vol. 10, 1884)
Strengths given in Pounds per Square Inch.

Kind of Stone.	Specific gravity.	Weight per Cubic Foot.	Cross-bending.		Compressive Strength.			Tensile Strength.	Shearing Strength.	
			Modulus of Elasticity.	Modulus of Rupture.	Perpendicular to Bed.	Parallel to Bed.	Parallel to Bed after 25 Freezings.		Perpendicular to Bed.	Parallel to Bed.
Granite	2.65	165.4	2,986,000	1365	19,200	18,910	21,470	619	1379	142
Granite	2.66	166	1,621,000	1194	19,200	20,050	20,480	683	1450	853
Triassic limestone	2.48	154.8	6,420,000	882	8,130	8,320	6,810	583	555	384
Jurassic limestone	2.23	139.2	....	...	11,110	7,410	12,290	448	739	540
(marble)	2.08	129.8	4,906,000	462	4,664	8,760	3,313	213	498	299
Oölitic limestone	2.72	169.7	....	1792	19,340	20,620	18,770	910	1479	1138
Tuffa stone	1.80	112.3	....	469	1,195	2,545	2,076	227	227	213
Variegated sandstone	2.06	128.5	426,600	469	7,420	6,010	6,730	107	569	355
Variegated sandstone	2.20	137.3	867,400	718	9,040	7,790	7,910	199	512	313
Variegated sandstone	2.28	142.3	1,340,000	1109	12,930	13,410	11,520	576	910	540
Variegated sandstone	2.00	124.8	341,300	341	6,160	6,100	4,877	128	455	427
Carboniferous sandstone	2.20	137.3	910,000	483	7,636	8,390	5,986	341	640	284
Carboniferous limestone	2.23	139.1	334,200	441	6,684	6,670	5,900	213	583	469
Slaty sandstone	1.82	113.6	512,000	249	3,071	2,247	2,161	98	370	242
Slaty sandstone	1.92	119.8	270,200	135	3,029	2,659	4,252	67	242	185
Green sandstone	2.15	134.2	583,000	156	4,707	4,308	4,038	94	341	327
Cretaceous sandstone	2.60	162.3	568,800	597	13,510	14,500	......	327	668	370
Cretaceous sandstone	2.73	170.4	2,687,000	967	28,860	17,490	......	512	995	768
Quartz conglomerate	2.29	142.9	1,763,000	654	5,546	4,408	3,270	242		

In Table 4 appear values of Poisson's ratio for stone. With one or two exceptions the values are about the same as those given for the ferrous metals; one-fourth is a fair average.

273. Resistance to Abrasion and Shock.—The abrasion on pavements, sidewalks, and doorsteps is a matter of considerable importance in determining the life of stone used for such purposes. A number of tests have been devised for measuring abrasive resistance, but none have been universally adopted. Two types of test have been considerably used. In one a carefully prepared stone specimen with a plane face is held against a horizontal table which revolves about a vertical axis, and abrasion is produced by sand or emery. In the other test a graded sample of crushed stone or gravel is subjected to abrasion in a rattler.

Bauschinger experimented considerably with the first method, using a cast-iron table 5 ft. in diameter. He placed two specimens each 4 in. square at a distance of 19.5 in. from the axis and weighted each with 30 kilograms. The table was run at a speed of 20 r.p.m. and 20 grams of fine emery (No. 3) was fed to the plate every 10 revolutions, the old emery being brushed off. Two attendants constantly kept the emery in the path of the specimen.*

The results of some of Bauschinger's preliminary tests to determine proper pressure and rate of feeding the emery are shown in Fig. 6. Table 6 shows the average results which he obtained in testing various materials. They indicate:

1. That the wet grinding was about twice as effective as the dry grinding, the exact average ratios being given in the last column of the table for each species of stone.†

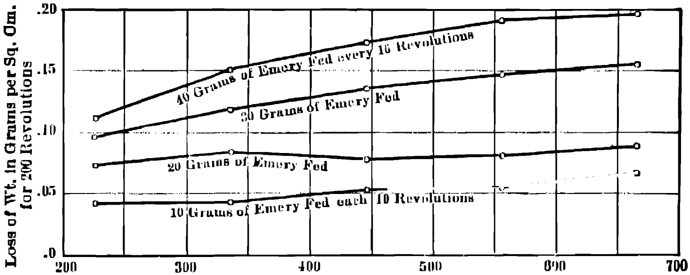

Fig. 6.—Showing the Relation between the Abrasion, Pressure, and Energy Used in Abrasion Test. (Bauschinger.)

2. There is no fixed relation between crushing strength and abrasive resistance.

3. The limestones wear about five times and the sandstones about four times as fast as the granites, porphyries, and basalts.

4. The clay-slate shows the best results in abrasion, but only a few specimens were tested.

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* Bauschinger's test does not differ greatly in principle from the Dorry hardness test used in France and the United States for road metal. In the Dorry test the abrasive agent is standard quartz sand passing a 30-mesh and retained on a 40-mesh sieve; the diameter of each specimen is 1 inch; and the speed is 30 r.p.m. for 1000 revolutions.

† These ratios have been taken from the wet and dry tests on identical material, and therefore are not the ratios of the two general average results in the previous column.

TABLE 6.—AVERAGE RESULTS OF BAUSCHINGER'S ABRASION TESTS OF PAVING MATERIAL

(*Communications*, Vol. 11, 1884)

Four-inch cubes of the material were pressed on an iron plate with a weight of 4 pounds per square inch, and 20 grams of emery fed every 10 revolutions. Results obtained for 200 revolutions at a radius of 19.5 inches.

Kind of Material.	Average Specific Gravity.	Average Weight per Cubic Foot in Pounds.	Average Compressive Strength in Pounds per Sq. in. Inch.	Number of Results Averaged.	How ground: Dry or Wet.	Average Loss of Volume in Cubic Inches.	Ratio: Loss wet / Loss dry
Granite....	2.63	164	22,400	92	dry	0.24	1.72
				8	wet	0.46	
Syenite..........	2.27	142	18,780	24	dry	0.28	1.90
				1	wet	0.82	
Diorite..........	2.87	180	26,200	18	dry	0.27	1.90
				2	wet	0.68	
Hornblende.......	2.82	176	21,900	2	dry	0.19	
Porphyry.........	2.57	161	24,500	93	dry	0.20	1.72
				8	wet	0.24	
Basalt...........	3.01	188	34,200	86	dry	0.19	2.31
				4	wet	0.47	
Gneiss...........	2.61	163	23,000	4	dry	0.21	
Quartz...........	2.63	165	17,500	9	wet	0.19	
Clay-slate........	2.72	170	26,000	8	dry	0.16	2.76
				2	wet	0.35	
Breccia..........	2.61	163	22,600	10	dry	0.20	
Limestone........	2.87	180	20,500	163	dry	1.10	1.60
				32	wet	1.41	
Sandstone........	2.48	155	17,600	44	dry	0.81	2.25
				38	wet	0.64	
Brick and tile.....	2.98	187	......	105	dry	0.38	2.50
				34	wet	0.75	
Artificial stone made with Portland cement...	2.36	148	......	20	dry	0.51	3.20
				4	wet	1.82	
Asphalt paving..	2.33	146	......	2	dry	0.61	2.68
				2	wet	1.62	

5. The brick and tile wear about twice as fast and the cement compositions about three times as fast as the primitive rocks.

6. The resistance of asphalt paving to abrasion falls between the cement mixtures and sandstone.

The introduction of the Los Angeles abrasion machine * marked an advance in methods of testing the wear resistance of crushed slag, or gravel. The machine consists of a cylindrical drum 20 in. long and 28 in. in diameter, inside, fitted with a removable dust-tight cover, mounted on horizontal trunnions which are co-axial with the drum. In this test a 5-kg. representative dry sample graded from 1½ in. to ⅜ in., or from ¾ to ⅜ in., in a standard manner is used. Along with the aggregate an abrasive charge of 5-kg. cast-iron spheres similar to those used in testing paving brick is introduced into the rattler drum. After 500 revolutions at 30 to 33 r.p.m. the charge is withdrawn and sieved on a standard No. 12 sieve. The loss in weight expressed in terms of the original sample is reported as the percentage of wear. On account of the size of the rattler drum and the impact of the abrasive charge the test also measures to some extent toughness.

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* See D. O. Woolf, *Proc. Highway Res. Board*, Vol. 16, p. 174; *Proc. A.S.T.M.*, Vol. 35, Pt. 2, p. 511; also A.S.T.M., *Standards*.

Extensive tests with this machine demonstrate that its indications agree with service records of materials tested. Test samples are easily prepared, the test is rapidly made, and the results are not influenced by the dust in the rattler or personal equation in the preparation of the sample. The influence of friable, soft, or elongated particles is also detected by this machine. Good aggregate for road work will usually show less than 30 per cent wear in this test.

The toughness of rock for road-construction * purposes is often measured by the Page impact machine. This device consists of a 50-kg. anvil at the base, upon which the cylindrical test sample 1 in. in diameter and 1 in. high is clamped, a 1-kg. plunger, which rests on top of the specimen, and a 2-kg. hammer mounted above the specimen and sliding in guides. The guides are so arranged that the hammer can be dropped at heights progressively increased by 1-cm. intervals. The toughness index for a stone is the height of the last drop causing rupture. Kessler † gives the following toughness ranges for stones: limestone 4–21; slate 10–56; sandstone 3–47; quartzite 14–30; serpentine 6–17; rhyolite 6–42; diorite 12–36; schist 6–34; granite 7–31. Rocks of low toughness give indices below 13, those of high toughness above 19.

Toughness tests of gravel can be made by subjecting a representative sample of 50 or more particles between ¾ in. and 2 in. in diameter to impact. The apparatus consists of a cast-iron base 1¾ in. high and 5 in. in diameter, from which protrude 3 vertical guide rods. A 2½-in. steel sphere resting on the base serves as an anvil upon which the gravel particles are held by the fingers. A similar sphere is used as a hammer. Particles of sedimentary origin having average minor diameters (d) should withstand without cracking blows from heights (h) as given by the relation $h=4(d-\frac{1}{4})$. For particles of igneous or metamorphic origin, the relation $h=4d$ should obtain.

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* See 6000 test results in U. S. Dept. of Agric. *Miscellaneous Pub.* No. 76.

† *Technologic Paper* No. 349, U. S. Bureau of Standards.

CHAPTER VIII

STRUCTURAL CLAY PRODUCTS[*]

274. Introduction.—Clay products form one of the most important classes of structural materials. In building construction, brick and terra cotta are desirable on account of their pleasing appearance, strength and durability. Partition and floor tile form walls and floors of light weight which possess high strength and resistance to fire. Paving brick make economical and durable, although somewhat noisy, pavements. Clay pipe on account of their durability, strength, light weight, and cheapness are successfully used in sewers, drains and conduits.

Structural clay products may be classified as follows:

- Brick
  - Building brick
  - Paving brick
  - Fire brick
- Building tile
  - Load-bearing tile
  - Bakup tile
  - Partition tile
  - Fireproofing
  - Roofing tile
  - Floor tile
  - Wall tile
- Terra cotta.
- Pipe
  - Sewer pipe
  - Drain pipe
  - Conduit pipe

The total value of the clay products produced in the United States, in 1936, was $136,249,772. Of this amount the value of common brick was 22 per cent; fire brick, 19.5 per cent; building tile, 18 per cent; sewer pipe, 9.2 per cent; vitrified brick, 1.6 per cent; front brick, 9.4 per cent; drain tile, 1.9 per cent, and architectural terra cotta, 1.9 per cent.

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[*] The following texts have been freely consulted in preparing this chapter: *Clays: Occurrence, Properties and Uses;* also *Building Stones and Clay Products*, by H. Ries; Wiley & Sons. *The Clay Workers' Handbook*, by A. B. Searle; Griffin & Co. *Modern Brick Making*, by A. B. Searle; Scott, Greenwood & Son.

MATERIALS, MANUFACTURE AND TESTING OF CLAY PRODUCTS

THE RAW MATERIALS

275. Classes of Raw Materials.—In addition to the various types of clay there are also many forms of shale which are used in the production of clay products. Clays are those substances resulting from the decay of rocks, which possess plasticity on being tempered with water and which are capable of retaining their shape when molded into various forms and dried. When such bodies are heated to redness or above they resemble rocks in hardness and strength. Shale is a hardened form of clay which has been consolidated by the weight of overlying earth, but which after being reduced to a powder exhibits the above-mentioned characteristics of clay.

Residual clays are formed from the decay of the underlying rocks. They constitute important sources of high-grade clays for pottery. Those clays which have been removed from the parent rock by glacial action, by water or by wind are called transported clays. Such clays are often termed sedimentary since they have been carried as sediment by the current and deposited in places where the velocity of flow decreased. On account of the changes in conditions which surrounded the deposition of sedimentary clays, they generally consist of strata of material which often vary considerably in composition and properties. Frequently such clays have sandy laminations or are mixed with sand.

Since the largest and most homogeneous deposits of sedimentary clay are those precipitated in large bodies of still water; the marine clays, deposited on former ocean bottoms, or lacustrine clays, found on the bottoms of extinct lakes or in swamps, form the most valuable sources of raw materials for the manufacture of structural clay products. The soft clays, either glacial or residual, which are found at or near the surface are often termed surface clays. Fire-clay is a term, loosely applied, to include those sedimentary or residual clays which vitrify at a very high temperature and which, when so burned, possess great resistance to heat. Impure fire-clays are contaminated with certain fluxes such as lime, iron oxide or the alkalies which reduce the vitrification temperature. In many of the coal-producing states fire-clays underlie the coal beds.

276. Composition of Clays.—In determining the suitability of clays for the manufacture of clay products a knowledge of both the mineral and chemical constitution is of assistance. From the mineral constitution the proportion of true clay substance may be gotten, whereas the chemical constitution affords indications of the purity, refractoriness, color, and shrinkage or swelling in burning.

The minerals most commonly found in clays and shales are kaolinite ($2SiO_2$, Al_2O_3, $2H_2O$) and other hydrated silicates of alumina; quartz

(SiO_2); feldspar (principally silicate of alumina combined with potash, or lime, or soda and lime); limonite ($2Fe_2O_3,3H_2O$); hematite (Fe_2O_3); siderite ($FeCO_3$); pyrite (FeS_2); calcite ($CaCO_3$); magnesite ($MgCO_3$); gypsum ($CaSO_4,2H_2O$), and sometimes rutile (TiO_2). Of these minerals, kaolinite and other hydrated silicates of alumina are the most desirable constituents. They generally form the major part of those high-grade clays, termed kaolins, which are used in the production of crockery and white burning pottery. These silicates constitute the finer portion of the clay which is called the clay substance. By Seger, clay substance is defined as the material less than 0.004 in. in diameter.

Chemical analyses of good clays will show that they consist mainly of the following elements:

Silica	(SiO_2)	
Alumina	(Al_2O_3)	
Ferric Oxide	(Fe_2O_3)	Fluxing Ingredients (generally less than 20 per cent)
Lime	(CaO)	
Magnesia	(MgO)	
Alkalies	(K_2O+Na_2O)	
Water	(H_2O)	
Carbon Dioxide	(CO_2)	
Sulphur Trioxide	(SO_3	

Silica generally forms from 40 to 80 per cent of the raw materials used in making structural clay products other than fire brick. In the latter the silica content may rise to 98 per cent. Although a large percentage of sand or uncombined silica in clay is undesirable, it is sometimes added to decrease shrinkage in burning and to increase the refractoriness of low alumina clays.

The alumina content ordinarily ranges from 10 to 40 per cent except in silica brick. Wares having an exceedingly high alumina content are likely to be very refractory.

Iron oxide, which in most cases constitutes less than 7 per cent of a clay, is a most important factor in determining the color of the clay and the burned product. It also tends to lower the fusion point of the clay, especially if present as ferrous oxide.

Lime normally constitutes less than 10 per cent of clay, but in some glacial deposits, which are successfully used in making common brick and tiling, a higher lime content obtains. In carbonated form lime lowers the fusion point. Since the carbonate breaks up into carbon dioxide (CO_2) and lime (CaO) at a temperature of 900° C.; it is desirable, in clays burned at this temperature, to finely crush the lime pebbles. If this is done, danger from "popping" in the burnt ware, due to slaking of the lime, may be avoided If the burning temperature is considerably higher than the above, complex combinations of lime, silica, and alumina are formed with the result that the lime effects a change in the color of the product. Red-burning wares are often made buff-burning by increasing the lime content.

Magnesia rarely exceeds 1 per cent in clay. In burning it causes the clay to soften at a slower rate than does lime and lessens warping.

The alkalies, forming less than 10 per cent of the raw clay, are of great value as fluxes, especially when combined with silicates of alumina. Feldspar is much used as a flux with kaolin in making white ware.

A large proportion of free water generally causes clay to shrink considerably in drying; combined water causes shrinkage in burning.

Carbonaceous material in the form of bituminous matter or carbon greatly affects the color of the raw clay. Unless proper precaution is taken to effect complete removal of such matter by oxidation, the burned product is likely to have a black core.

Sulphur is most commonly found in clay as the sulphate of calcium, magnesium, potassium, sodium or iron, or as iron sulphide. Generally the proportion is small. If, however, there is carbon in the clay and insufficient time is given during burning for proper oxidation of carbon and sulphur, the latter will cause a spongy swollen structure in the burned product. Most of the sulphates are soluble and give evidence of their presence by the formation of a scum on the dried ware. As a result, unless considerable care is exercised in burning, the product will be discolored by white blotches. The use of water containing small quantities of magnesium or calcium carbonates, together with a sulphurous fuel often causes similar effects. Wall white, which appears after brick have been laid, may be due to soluble salts in the brick or in the mortar, which are brought to the surface by absorption of water and subsequent drying.

277. Physical Properties of Clays.—Plasticity, tensile strength, texture, shrinkage, porosity, fusibility, and color after burning are the physical properties which are of most importance in determining the value of a clay. A knowledge of these properties is of more benefit in judging the quality of the raw material than a chemical analysis.

By plasticity is meant the property which wetted clay has of being permanently deformed without cracking. The amount of water required by different clays to produce the most plastic condition varies from 15 to 35 per cent. Although plasticity is probably the most important physical property of clay, yet there are no methods of measuring it which are entirely satisfactory.* The simplest and most used test is afforded by feeling of the wetted clay with the fingers. Personal equation necessarily plays a large part in such determination.

Since clay ware is subjected to considerable stress in molding, handling, and drying a high tensile strength is desirable. The test is made by determining the strength of specimens which have been molded into briquette form * and very carefully dried. The tensile strength of clays will vary from almost nothing in highly silicious fire clays to over 400 lb. per square inch in some common brick clays. Kaolin generally shows low tensile strength.

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* For a more complete discussion of the physical properties and their measurement, see *Clays, Their Occurrence, Properties, and Uses*, Third Edition, by H. Ries, Chapters IV and V.

The texture of a clay is measured by the fineness of its grains. In rough work the per cent passing a No. 100 sieve is determined, but for measuring the size of the clay grains a more refined device such as the Schöne washing apparatus or a centrifugal separator is used. No numerical limit to the grain size or desired relation between sizes has been established. Tests by Beyers and Williams † indicate that the sizes of grain from 0.004 in. down should be uniformly graded to obtain maximum tensile strength. Ries' tests showed that an excess of either very fine material or of sand grains decreased the tensile strength of the clay. Very fine-grained clays free from sand are more plastic and shrink more than those containing coarser material.

A knowledge of the shrinkage both in drying and in burning is required in order to produce a product of required size. Also the amount of shrinkage forms an index of the degree of burning. The shrinkage in drying is dependent upon pore space within the clay and upon the amount of mixing water. The addition of sand or ground burnt clay lowers shrinkage, increases porosity and facilitates drying. Fire-shrinkage is dependent upon the proportion of volatile elements, upon texture and the way that clay burns. Tests of shrinkage are made by determining the volume of benzine displaced by a small prism of clay when green, after drying at a temperature slightly above the boiling point of water, and also after burning. Beyer and Williams, in tests on a number of Iowa clays, reported air-shrinkages varying from 4.86 per cent to 27.00 per cent and fire-shrinkages from −2.88 per cent (swelling) to 5.92 per cent.

By porosity of clay is meant the ratio of the volume of pore space to the dry volume. Since porosity affects the proportion of water required to make clay plastic, it will indirectly influence air-shrinkage. Large pores allow the water to evaporate more easily and consequently permit a higher rate of drying than do small pores. Inasmuch as the rate at which the clay may be safely dried is of great importance in manufacturing clay products, the effect of porosity on the rate of drying should be considered.

The temperature at which a clay fuses is determined by the proportion of fluxes, texture, homogeneity of the material, character of the flame, and its mineral constitution. Owing to non-uniformity in composition, parts of the clay body melt at different rates so that the softening period extends

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* See briquette molds and testing machines in Ch. XII.

† *Iowa Geol. Surv.*, Vol. 15, p. 102, 1904.

over a considerable range both of time and temperature. Wheeler divides the period into (1) incipient vitrification, at which the clay has softened sufficiently to cause adherence but not enough to close the pores or cause loss of shape—on cooling the material cannot be scratched by the knife; (2) complete vitrification, more or less well-marked by maximum shrinkage, coalescence of particles, smooth fracture and no loss in shape; (3) viscous vitrification, produced by a further increase in temperature which results in a soft molten mass, a gradual loss in shape, and a glassy fracture after cooling.

Experiments roughly indicate that the higher the proportion of fluxes the lower the melting-point. Fine-textured clays fuse more easily than those of coarser texture and the same mineral composition. The uniformity of the clay mass determines very largely the influence of various elements; the carbonate of lime in large lumps may cause popping when present in small percentages, but when finely ground 15 per cent of it may be allowed in making brick or tile. Lime combined with silicate of alumina (feldspar) forms a desirable flux. Iron in the ferrous form, found in carbonates and in magnetite, fuses more easily than when present as ferric iron. If the kiln atmosphere is insufficiently oxidizing in character during the early stages of burning, the removal of carbon and sulphur will be prevented until the mass has shrunk to such an extent as to prevent their expulsion and the oxidation of iron. When this happens a product with a discolored core or swollen body is likely to result.

Since a determination of the fusibility of a clay is of much importance both in judging of the cost of burning it and in estimating its refractoriness, experiments are often made on small prisms to determine the rapidity with which the clay may be burned, the temperatures at which incipient, complete and viscous vitrification occur, how the clay behaves in annealing and the color of the burned product. Temperatures are commonly measured by means of Seger cones,* in refined work by a pyrometer.

METHOD OF MANUFACTURE

278. Preparation of the Clay.—Many of the large deposits of clay or soft shale are worked in open cut with a steam shovel. The hard shales adjacent to coal veins are frequently mined. Generally the raw material is drawn from the pit in cars on a narrow-gage track by horses or by dinky engines. For pressed brick and terra cotta it is sometimes advantageous to weather the clay, before using it. This is accomplished by loosely spreading the clay in a layer a couple of feet thick over a flat surface where it will be exposed to the action of the elements. Such action causes a rusting of iron particles and a breaking down of pyrite inclusions.

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* Seger cones are made from mixtures of clay and fluxes so proportioned that their melting-points form a temperature scale. Two or more cones differing in fusibility are inserted in the furnace or kiln and the temperature estimated from their appearances.

Most clays, however, are hauled directly to a crushing or disintegrating device. For the hard shales jaw-crushers are sometimes used. Dry pans like the one shown in Fig. 1 are often employed to break up the softer shales and tough clays. For certain dry shales, toothed or corrugated rolls are effective where coarse grinding only is required. After the clay has been crushed it is conveyed to a pug-mill (Fig. 2) in which it is tempered with the proper amount of water and thoroughly mixed. Wet clays are generally ground and tempered simultaneously in large ring pits, in pug-mills or in wet pans. In the ring pits a heavy iron wheel which rolls over the bottom surface of the pit in a spiral path, serves to stir and grind the

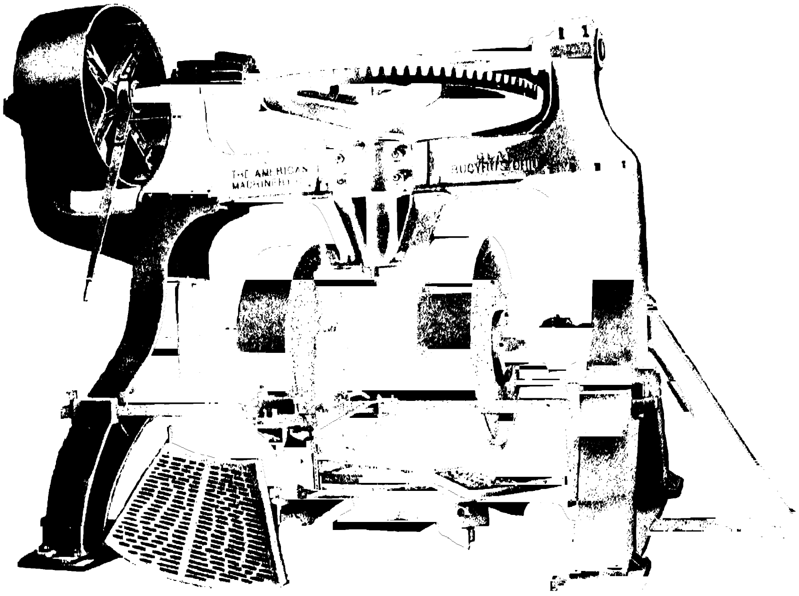

FIG. 1.—A 9-ft. Dry Pan.

FIG. 2.—A Double-shaft Pug Mill.

clay. This method is used only at small plants. The wet pan is much like the dry pan, with the exception that the bottom of the wet pan is not perforated.

279. Molding.—Building brick are molded by the soft-mud, the stiff-mud, or the dry-press process. The stiff-mud process is employed in making nearly all other structural clay products. Fire-brick is sometimes made by the soft-mud process and roofing, floor, and wall tile by the dry-press process.

In the soft-mud process the clay, or mixture of clayey materials, is tempered with enough water to form a mass of soft consistency. The mixture is then introduced into wooden molds which are lined with sand to avoid sticking. Either hand or machine molding is employed in this process. Soft-mud brick exhibit five sides to which more or less sand adheres. The soft-mud process can be used with a greater variety of clays than any other method of molding and very uniform brick may be made with it.

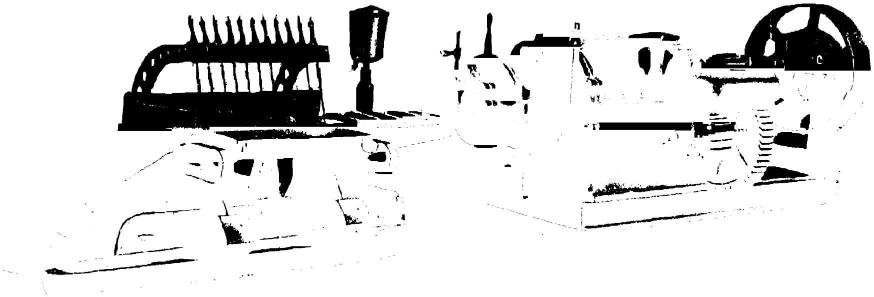

FIG. 3.—A Small Auger Equipped with Device for Making Side-cut Brick.

Less water is used in the stiff-mud process so that the mixture is much more rigid than in the soft-mud process. It is well applied to mixtures which are of medium plasticity. The clay from the pug-mill is forced through a tapered die by means of an auger and the issuing bar is cut into the required lengths. Owing to the motion imparted by the auger and friction on the sides of the die, various portions of the clay bar are given different velocities; consequently more or less laminations are present in the product of auger machines. Brick are made either end or side cut by this machine. Fig. 3 shows a side-cut machine. Auger brick machines have considerably greater capacities than the machines of the vertical press type used in the soft-mud or dry-press processes. For molding common brick, machines equipped with double or triple dies are sometimes used. Partition tile, conduits, fireproofing and the smaller sizes of drain tile are molded in a similar manner to stiff-mud brick. For sewer pipe and the larger sizes of drain tile, vertical presses are employed. The uniformity in shape and size of stiff-mud or soft-mud brick can be improved, the surfaces made smoother and harder, and the density and strength increased by repressing. This auxiliary process is often employed in making high-grade face brick and in molding paving brick.

In the dry press process the tempered clay is pulverized, screened through a No. 16 sieve, and then fed into molds on a vertical press. The molds of hard steel are steam-heated to prevent adherence of the clay. Vents are provided to allow the escape of entrapped air. Owing to the heavy pressures used, it is possible to obtain pieces with sharp corners and of more uniform shape than can be gotten from auger machines. This process also does away with air drying although considerable free water must be driven off in the kiln. Face brick are commonly dry-pressed.

Improvement in the uniformity, density, strength, and toughness of certain stiff-mud and dry-pressed clay products has recently been effected in the laboratory by de-airing. This is accomplished by often using high pressures in repressing or by evacuating air just before the clay is molded or passes in to the die of the auger machine. De-airing has been successfully applied in the manufacture of paving brick.

Terra cotta is generally hand-molded or cast in plaster molds.

✓ **280. Drying.**—Great care is required to dry soft-mud and stiff-mud products at maximum rate without causing checking. In some yards the open-air driers are provided with roofs, which can be opened during fine weather, and are means for heating in bad weather.

Artificial driers are of two types, the hot-floor drier and the tunnel drier. The former is the older and is used for fire brick, clay pipe and terra cotta. The hot-floor drier is heated either by a furnace placed at one end of the drier or by exhaust steam from the engine used to furnish power. Tunnel driers are periodic—filled, dried, and emptied in rotation—or continuous—the green ware being loaded into one end of the tunnel and the dried product removed at the other. Tunnel driers are heated by flues underneath, by steam pipes, or by hot air from cooling kilns. They are more economical than hot-floor driers. In artificial driers the temperature rarely exceeds 120° C. The time required in drying varies from one to three days, depending upon the temperature of the drier, the character of the clay, and the shape of the body.

In some brick plants the green ware is set in a kiln and dried by waste heat from cooling kilns. This method requires more kilns, but effects a saving in handling of brick.

✓ **281. Kilns.**—In the brick industry four types of kilns are in use: the scove kiln, the up-draft kiln, the down-draft kiln, and the continuous kiln. Of these types the down-draft and continuous kiln are used in burning other clay products. Terra cotta is generally burned in round down-

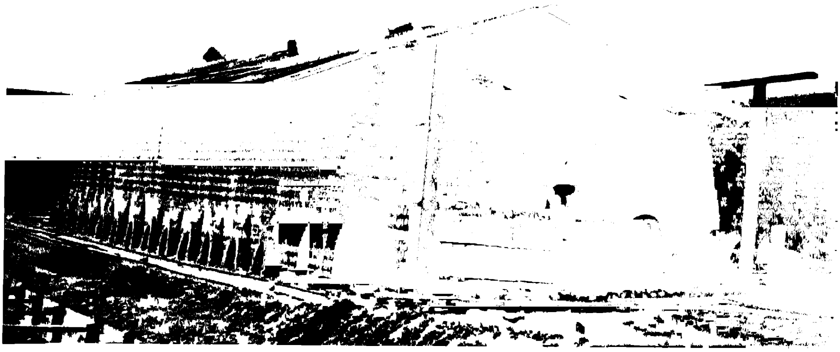

FIG. 4a.—Setting a Stove Kiln. Temporary End and Side Walls Not in Place. (*Bull.* No. 15, Wis. Geol. and Nat. Hist. Surv., Pl. 6.)

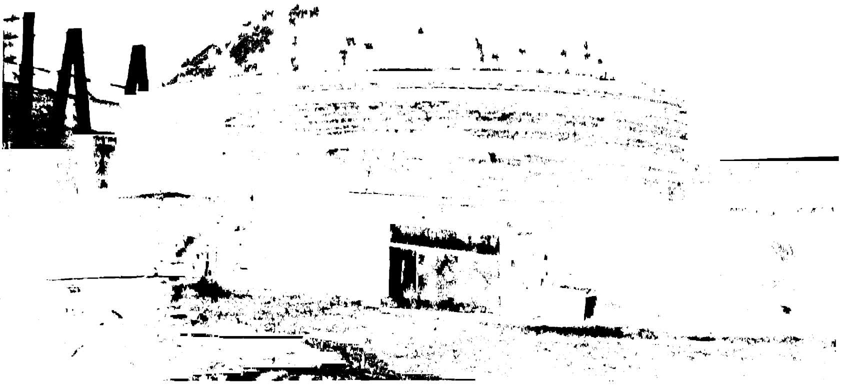

FIG. 4b.—Circular Down-draft Kiln Used for Burning Brick. (*Bull.* No. 15, Wis. Geol. and Nat. Hist. Surv., Pl. 6.)

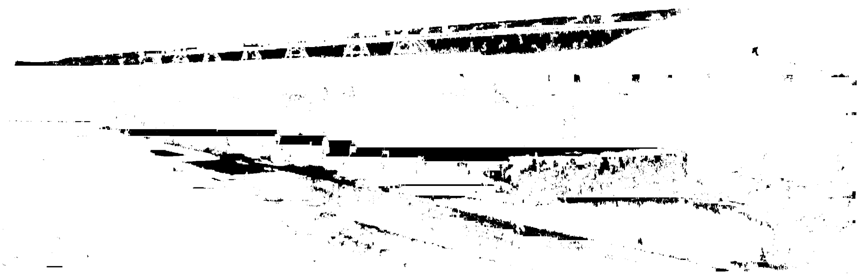

FIG. 4c.—Haigh Continuous Kiln (American Clay Machinery Co.)

FIG. 4.—COMMON TYPES OF KILNS.

draft kilns provided with muffles to prevent contact of flame and ware.

The scove kiln shown in Fig. 4*a* is much used in burning common brick. Brick are laid about 40 courses high and the entire kiln enclosed with a course or two of special brick containing a small proportion of coal. The outside is then plastered with mortar and fires started in the arches. Wood or oil is used as fuel. The temperature of the outer and inner portions of the kiln is equalized to some extent by the combustion of the coal-brick. Although the cost of the scove kiln is low, the loss in brick and in heat is high.

Up-draft kilns provided with permanent walls and roof are an improvement over the scove kiln, but they are more wasteful of heat and are heated less uniformly than the down-draft kiln.

The down-draft kiln (Fig. 4*b*) is either rectangular or circular in plan, the former being used largely in burning the better grades of building brick and in burning paving brick. As the name implies, heat from the fire after passing through up-takes to the top of the furnace is drawn downward through the kiln and passes through flues in the floor. Thence the waste gases are led through tunnels either to a stack passing up through the center of the kiln, or to a detached stack serving several kilns. With the down-draft kiln a more uniform distribution and better regulation of heat can be obtained than with either of the previously described kilns. Since the hardest burned ware, which becomes the softest in burning, is found at the top of the kiln, it cannot be misshapen by the weight of overlying courses.

Continuous kilns (Fig. 4*c*), are often built oval in plan and divided by vertical walls into a large number of compartments. These are loaded from the interior of the ring and unloaded from the outside. Each compartment is provided with an adjoined fire-box, a flue leading to a central stack and by-passes in the side walls through which the compartment can be connected with the adjacent compartments. Pockets are also provided in the top of each chamber for additional fires. Chambers are charged, fired, and unloaded in rotation. A chamber is first isolated and heated by the side fire-box until the ware is freed of combined water. Then the waste heat from the adjoining chamber is admitted until a red heat is attained when the top pockets are fired until burning has been completed. This type of kiln effectively utilizes fuel and is used to burn brick, fire proofing, and tile.

Terra cotta and brick are sometimes loaded on cars and burned in gas-fired tunnel kilns. The dried ware is entered at one end and as it is slowly moved through the tunnel the temperature is raised to the maximum desired at mid-length, and then gradually reduced as the ware reaches the exit. In this form of continuous kiln the temperature control is excellent and the product uniformly burned.

282. Burning.—The burning of clays may be divided into three main stages: (1) dehydration or "water smoking," (2) oxidation, (3) vitrification, or period of settlement in the kiln.

During the dehydration period the water which has been retained in the pores of the clay after drying is driven off, some of the carbonaceous matter is burned, a portion of the sulphur is distilled from pyrites, hydrous minerals like kaolinite and ferric hydroxide are dehydrated, and the carbonate minerals are more or less decarbonated.* The speed with which these eliminations occur is dependent upon the water and mineral content of the clay, its porosity, and its texture, and upon the method of handling the kiln. Too rapid heating causes cracking or bursting of the ware. On the other hand, if alkali is contained in the clay or much sulphur is present in the coal, too slow heating produces a scum on the surface of the product. During the "water-smoking" stage, frequent measurements of the draft and temperature are made in order to standardize the procedure for a given clay. This period is generally completed before a temperature of 700° C. is reached.

During the oxidation period, which is nearly always completed at 900° C., the remainder of the carbon must be eliminated and, to promote stability, the ferrous iron must be oxidized to the ferric form. Although some of these changes begin before the completion of the preceding change, it has been pretty well demonstrated that the removal of sulphur cannot be completed before the carbon has been eliminated. Sulphur, on account of its affinity for oxygen, also holds back the oxidation of iron. Consequently, in order to avoid black or spongy cores, oxidation must proceed at such rate as will allow these changes to occur before the heat becomes sufficient to soften the clay and close its pores. Grog or sand is often added to the raw clay to produce a more open structure and thus provide for the escape of gases generated in burning.

The different stages in vitrification have already been mentioned. It should be borne in mind that but few clay products are vitrified to the point of viscosity, indeed, many common brick and tile cannot be called vitrified in any sense of the term. On the other hand paving brick must be burned to the stage which Wheeler calls complete vitrification if the maximum combination of hardness and toughness is to result. There is, consequently, a wide range in the maximum burning temperature to which the clay must be submitted depending upon the character of the raw material and the purpose of the ware. In the manufacture of tile and building brick this range varies between 900 and 1200° C.

The degree of burning is frequently determined by the settlement of the goods in the kiln, in some cases by pyrometers. For ware which is to be completely vitrified, it is advantageous to have the points of incipient and viscous vitrification separated as widely as possible. This is desirable in order that goods from different parts of the kiln may not vary widely owing to non-uniform distribution of heat.

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* Prof. E. Orton, Jr. *Trans. Am. Ceramic Soc.*, Vol. 5, p. 393.

283. Glazing.—By glazing clay products, it is possible to give a pleasing appearance to the ware, to increase its imperviousness to water, or to accomplish both of these ends without incurring the cost of complete vitrification. Slip-clays, which have a high fluxing content and which may be so adjusted in composition that different coloring effects can be produced, lead compounds, barium compounds, and common salt are among the substances used for glazes. Decorative terra-cotta goods are sprayed with a thin mixture of slip-clay before burning. Sewer pipe is salt-glazed by the addition of common salt to the fires during the vitrification stage. Enamel brick are given a coating of slip containing oxide of tin or similar compound to render the glaze opaque.

284. Flashing.—Colors ranging from gold to dark reddish brown may be produced on many kinds of ware by flashing. The process consists in exposing the ware to a reducing atmosphere during a part or whole of the burning period. Front brick are often so treated with pleasing results. Flashing, however, is likely to deceive even experts concerning the degree of burning.

285. Annealing.—Great care is necessary in cooling the goods below a cherry-red heat in order to avoid checking and cracking. Hastening the annealing process may destroy the product of an otherwise successful burn. To make paving brick of maximum toughness requires an annealing period of seven to ten days.

286. Sorting.—In up-draft kilns the over-burned ware is found at the bottom near the top of the arches and the under-burned material is at the top. The converse is true for down-draft kilns. In either kiln, the best of the product is found in the intermediate courses. In the manufacture of paving brick, high-grade building brick, and drain tile, these different classes of goods are separated in unloading the kiln and the poorer grades of material sold for different purposes. Over-burned paving-brick and building brick are used in sewer construction. Soft-burned paving brick are used for exterior walls in building construction, while the soft-burned building brick serve as filling.

METHODS OF TESTING STRUCTURAL CLAY PRODUCTS

287. Tests.—Two classes of tests are used in judging of the quality of clay products: (*A*) tests which may be readily made on the job; (*B*) those which require laboratory equipment. The field tests are: (1) appearance, (2) hammer test, (3) hardness, (4) absorption, (5) specific gravity. In the laboratory, the following additional tests are sometimes made: (6) crushing, (7) transverse bending, (8) rattler test * (paving brick), (9) abrasion (paving brick), (10) resistance to freezing and thawing. (Arts. 264 and 296.)

288. Appearance.—Shape, color, kiln marks, checks, laminations and blisters all form more or less valuable indications of quality. The color of the outside of the goods is often misleading in regard to the degree of burning. This also applies to the color of the interior, unless one is familiar with the changes which the given clay undergoes in burning. The presence of lime pebbles over $\frac{1}{8}$ in. in diameter is undesirable. Black or spongy cores show improper burning as previously mentioned. In brick, well-defined kiln-marks indicate that the brick have been hard burned, but do not serve to distinguish between hard-burned and over-burned brick. Checks and cracks may be due to improper drying or annealing. They decrease the strength and resistance to frost; if well-marked they are sufficient cause for rejection. Checks produced in annealing generally indicate brittleness. Pronounced laminations in the cross-section of the ware are objectionable since they weaken the structure and lessen resistance to freezing. Broken blisters on the surfaces of sewer pipe or drain tile are due to air imprisoned in molding. They should not be tolerated on the inner surface. When present on the outer surface they should not exceed $\frac{1}{5}$ of the thickness of the tile in depth, nor in diameter should they exceed $\frac{1}{8}$ of the diameter of the pipe.

289. The Hammer Test. When properly burned and free from cracks, dry clay products emit a highly metallic ring if struck with a hammer. A rough notion of the toughness of brick is also afforded by breaking specimens with the hammer.

290. Hardness.—To secure evidence of the degree of burning, the interior of the clay body may be scratched with a knife. Sewer pipe and paving brick which have been burned to incipient vitrification or above cannot be scratched. Well-burned tile will be scratched with difficulty.

291. Absorption.—The percentage of absorption is a very valuable indication of the degree of burning provided one knows the limit of the given clay corresponding to a properly burned product. According to Orton † vitrification, in the true sense, corresponds to such a degree of compactness that the absorption of the product is not over 3 per cent after forty-eight hours' immersion. He also stated that if the absorption was less than 5 per cent danger from frost was negligible. Since the expansive force of water freezing in the pores of a clay material is dependent upon the proportion of pore space occupied, the ratio of the absorption after 24 hr. submersion to absorption after boiling 5 hr. (C_{24}/B_5 ratio) appears to be a better criterion of resistance to freezing than the percentage of

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by 1.50; if

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* S

ce-point bearing n

† 5, p. 263.

absorption (Art. 300). McBurney's recommendations on methods for procedure in absorption tests in *Proc. A.S.T.M.*, Vol. 36, Pt. 1, p. 260, should be studied.

Tests by Palmer and Parsons * show that bricks in condition to absorb 10 to 35 grams of water in 1 min. when immersed $\frac{1}{8}$ in. on one face develop the strongest mortar bond. Too rapid withdrawal of water from the mortar by brick produces a weak bond. These tests and others indicate that the suction rate is an important property of brick and tile. It should be controlled by the manufacture and builder and determined on the job.

No standard method of making the absorption test has been adopted for all structural clay products. Five half brick from different units or 15 uncracked square fragments of structural clay tile, drain tile, or sewer pipe selected from five units constitute suitable samples for the respective materials. The fragments should be 12 to 20 sq. in. in area. In all procedures specimens should be oven-dried to constant weight at temperatures just above the boiling point of water. Usually a temperature of 110 to 120° C. for 72 hr. is sufficient. Weighing should be done on scales sensitive to 0.1 per cent of the weight of the specimen. Where the *C/B* ratio is to be determined, as for brick, specimens are submerged for 24 hr. in distilled, or rain, water at room temperature (15 to 30° C.) and carefully surface-dried with a towel before weighing. They are then boiled for 5 hr. in distilled, or rain, water, cooled in the water, and again surface-dried and weighed. The difference between weights after soaking or boiling and the dry weight divided by the dry weight and multiplied by 100 gives the weight percentage of absorption. Absorption after boiling is prescribed by the A.S.T.M. (see *Standards*) for the following intervals: for structural clay tile, 1 hr.; for drain tile and sewer pipe, 5 hr.

If the absorption by volume is desired, it can be obtained by multiplying the weight percentage by the apparent specific gravity.

292. Specific Gravity.—Other factors constant, the higher the bulk specific gravity the stronger is the clay product. This rule does not hold for vitrified products since Purdy and Moore's tests † show that the specific gravity of a clay decreases as vitrification advances. *Specific gravity* may be determined on the pulverized product (Art. 268). It is often less accurately found by dividing the dry weight in air by the difference between the dry weight and the weight when submerged cold after boiling 5 hr. The *bulk specific gravity* may be found by dividing the dry weight in air by the difference between the weight saturated in air and the weight saturated whe[illegible]d.

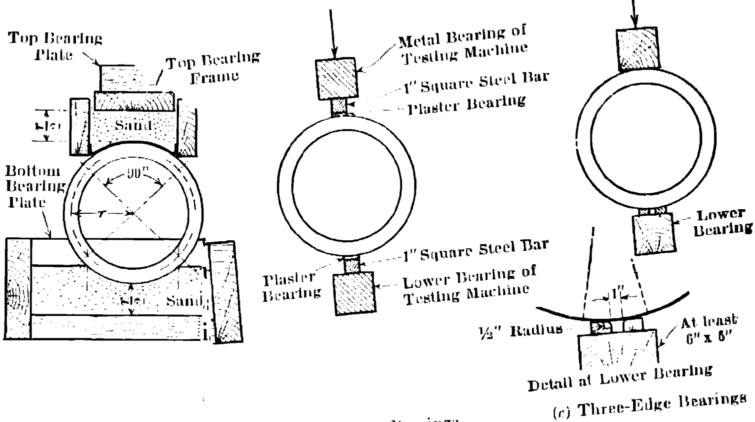
293. Str[illegible] methods of making the crushing and transverse tests [illegible]ng [illegible] are the same as outlined in Art 112

Proc. A.S.T.M., Vol. Art. 294 See to

[illegible]) absorption, Bur. Stds.

[illegible]ional tests are som[illegible] p. 203.

The crushing test is generally made on half brick bedded flatwise, s method is not satisfactory both on account of the uncertainty in ining the final load and on account of the lack of opportunity for ailure. These considerations have led some experimenters to bed k on the edges. The strength of side-cut brick on edge is some-) to 60 per cent less than the strength of specimens bedded flatwise. crushing test affords a means of comparing the quality of brick or is of little value in determining the strength of a wall, since the latter primarily on the strength of the mortar. As a criterion of struc- ength for brick, the transverse test is of more value than the crush- since transverse failure in a wall or pavement is likely to occur on of improper bedment. Brick which are improperly annealed or



(a) Sand Bearings (b) Two-Edge Bearings (c) Three-Edge Bearings

Fig. 5.—Methods of Supporting Drain Tile for Strength Tests. (*A.S.T.M.*, Des. C4-24)

checked in air-drying exhibit a lower transverse strength than properly treated specimens. Moreover, the transverse test can be made in a small machine without the expense of a bedment.

Drain tile and sewer pipe are often tested under gradually applied loads placed as indicated in Fig. 5. The tile should be thoroughly wet when tested and not less than five specimens should be tested. The supporting strength (W) is defined as the load per lineal foot which the tile can carry when loaded through sand bearings. Under this condition the moment, $M = \frac{0.20RW}{12}$, wherein R is the radius of the center line of the tile in inches. To determine supporting strength from a three-point bearing test, multiply the breaking load per foot by 1.50; if hydraulic bearings are used multiply by 1.25. The three-point bearing method is simpler in application, but it is more severe on warped pipe than either hydraulic or sand bearing. Sand bearings also approximate quite closely the loading conditions to which the pipe is subjected in a ditch.*

294. The Rattler Tests on Paving Brick.—Although the rattler test
has never been shown to be a true index of the life of brick in a pavement,
yet as a means of standardizing resistance of paving brick to combined
impact and abrasion it is considered valuable. For details in performing
this test, see A.S.T.M. current *Standards*. The test consists in placing one
representative sample of 10 whole brick which pass visual inspection
requirements in a metal barrel 20 in. long and 28 in. in diameter, together
with a 300-lb. charge of cast-iron spheres, and subjecting the bri
the action of the charge during 1800 revolutions at 30 r.p.m. Tunits to
is mounted on horizontal axial trunnions which are parallel to e barrel
Openings between the 14 staves of the barrel permit escape ne the sides.
pavers 3 by 4 by 8½ in. in size will usually show less tha dust. Good
in this test, although 24 per cent is permitted by the on 21 per cent loss

295. Pavement Determinators.—Numerous lal Specifications.
pavements have been made. Usually the samples oratory tests of sample
form segments of a circular track which rests on af the types of pavement
The abraiding apparatus consists of one or more loa permanent foundation.
be shod with rubber tires or more abrasive devided wheels, which may
rolled over the track in paths of variable radii thro s. These wheels are
vertical axle in the center of the track. After a suit h connection with a
cycles the condition of the pavement is examined v ble number of rolling
wear is sufficient measurements are made. ually, and where the

One of the earliest of these determinators was
Detroit. The Road Research Laboratory at Harn used by the city of
has 3 tracks, the largest of which operates a 10-ton tu ndsworth, England,
with a mean diameter of 110 ft. The U. S. Bureau ıck chasis on a track
the Crushed Stone Association also have tracks for s of Public Roads and

296. Alternate Freezing and Thawing Test.—C .ch tests.†
A.S.T.M. has prescribed an alternate freezing an mmittee C–6 of the
drain tile which may be applied to other clay produc l thawing test * for
on three or more specimens from each of five separate ti . The test is made
are so chosen that they represent the ends and center les. The specimens
must be sound, approximately square, and between of each tile. They
area. After being dried to constant weight at 110° C 12 and 20 sq. in. in
cimens are cooled to 20° or 25° C., reweighed, and imm ., or above, the spe-
For freezing the specimens are placed with their conc ersed in pure water.
ve faces upward in

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* For more complete information see Standard Specifications for Dr
Designation: C4-24, *A.S.T.M. Standards*. Tile, Serial

† See *Engr. Record*, Vol. 68, p. 457; *Highways and Bridges*, Apr. 29, 1936,
Roads, Jan., 1934; *The Crushed Stone Journal*, Dec., 1935. *Public*

trays of ice water. After the specimens have acquired the temperature of the water, the latter should be drawn off until ½ in. remains in each tray. The trays are placed in a suitable rack and immersed in a freezer. The freezer temperature must be reduced to −10° C. or below within thirty minutes after the specimens are introduced, but should not fall below −20° C. during the test. After the water in the trays has been frozen solid the trays are taken out of the freezer and immersed in water at a temperature of 18° to 24° C. The specifications demand 24 alternate freezings and thawings for Farm Drain Tile, 36 for Standard Drain Tile, and 48 for Extra Quality Drain Tile. Failure in this test is conditioned by (1) superficial disintegration or spalling with a loss of more than 5 per cent of the dry weight, or by (2) cracking badly in other than planes of laminations, or by (3) serious loss in structural strength.

PROPERTIES OF STRUCTURAL CLAY PRODUCTS

Building Brick

297. Manufacture.—A variety of clays are used in making building brick ranging from the common surface clays used for common brick to the better grades of shale or impure fire-clays used in producing face brick. The essential properties of the clay are sufficient plasticity for proper molding, low shrinkage in drying and burning, and low fusibility. The clay should not crack or warp during the drying or burning processes and for face brick or ornamental brick it should burn to a uniform color.

Common brick are frequently burned in scove kilns, but the better grades of building brick are fired in permanent kilns of the up-draft or down-draft type. The temperature of burning varies from 900 to 1200° C., depending upon the composition of the clay.

298. Classes of Building Brick.—Brick are often classified by method of molding as soft-mud, stiff-mud, dry-pressed, or re-pressed brick.

By the degree of burning, brick are sometimes sorted into three classes (1) pale or salmon brick which are underburned, (2) body brick which occupy the central portion of the kiln and are well-burned, (3) arch or clinker brick which are overburned.

Two irregular forms of brick commonly used in construction are compass brick and feather-edge brick. Compass brick have tapering broad faces; feather-edge brick have tapering narrow faces.

Cored brick extruded with 14 or 16 holes normal to the broad faces are easily and uniformly burned and light in weight.

From the standpoint of usage, the following classification may be made: common brick, front brick, and ornamental brick. Common brick comprise the poorer grades of building brick which are used for filling, backing, and in walls where appearance is of small moment. They often vary greatly in color, degree of burning, and in shape. Front or face brick are made more carefully than common brick. They are generally pressed or re-pressed and are used in fronts of buildings and in walls for which a pleasing appearance is desired. Red, white, cream, buff-burning brick, and buff-burning brick speckled by the addition of manganese, all of which burn to an even tone, are much used as front brick. Tapestry brick, rug brick and stipple-faced brick are stiff-mud products which have had their edges roughened in different ways in order to create pleasing effects in wall constructions. Ornamental brick include enameled and glazed brick. The former constitutes the major portion of the ornamental brick produced in the United States.

299. Requirements of Good Brick.—The essential requirements for building brick are sufficient strength in crushing and bending, durability, a proper suction rate,* and a pleasing appearance when exposed to view. Common brick of good quality should be free from checks or cracks, should emit a metallic ring when struck with the hammer, and should exhibit a fine-grained, uniform, dense structure free from laminations or large lime pebbles. Well-burned face brick should not be easily scratched by the knife. They should possess the previously mentioned characteristics, and also be uniform both in color and size. Regularity in size of brick and joints is important where high wall strength is required. Good brick should be free from soluble salts which cause efflorescence, such as the sulphates of lime, magnesia, and the alkalies. The liability to effloresce may be determined by allowing 3 or more bricks to stand on end immersed in ½ in. of distilled water for a week and then noting the appearance of the upper portions.

In a structure the durability of brick may be tested by frost action, by alternate wetting and drying, and by fire. Tests of fire resistance are generally made on wall-panels. Resistance to frost action is best ascertained from alternate freezing and thawing tests, which are, however, quite expensive. The absorption test has long been considered a measure of durability, although the basis for this assumption is questionable.

As indicated in Art. 291, the suction rate of a brick at the time it is laid exercises a marked influence on mortar bond. Although the suction rate can be regulated by wetting prior to laying, such procedure is always a nuisance and impracticable in cold weather. Hence bricks which in normal condition have suction rates between 10 and 35 grams per brick per min. are preferred for their superior bonding qualities.

The standard size for common and rough-face building brick of shale or clay is $8 \pm \frac{1}{4}$ by $3\frac{3}{4} \pm \frac{1}{8}$ by $2\frac{1}{4} \pm \frac{1}{16}$ in.; for smooth-face brick the width is $3\frac{7}{8} \pm \frac{1}{8}$, with other dimensions the same.

300. Tests on Building Brick.—A summary of tests on building-brick samples from 255 plants located throughout the United States and representing 37 per cent of the 1929 production is reported in Table 1. These

TABLE 1.—WEIGHTED AVERAGES OF STRENGTH AND ABSORPTION FOR BUILDING BRICK FROM VARIOUS PLACES IN THE UNITED STATES (McBurney and Lovewell).

District or City	Type of Brick	Average Compressive Strength, lb. per sq. in.	Average Modulus of Rupture, lb. per sq. in.	Average Water Absorption, per cent			Average Ratio, $\frac{C_{48}}{B_5}$
				5 hr. Cold	48 hr. Cold	5 hr. Boiling	
Maine, New Hampshire and Vermont	Hard	10,330	1505	5.7	6.3	8.7	0.70
	Salmon	5,520	995	13.9	14.5	17.2	0.84
Boston, Mass.	Hard	8,240	1360	7.7	8.2	10.6	0.74
	Salmon	3,710	645	16.4	17.1	19.6	0.88
Massachusetts, except Boston	Hard	5,940	1100	9.8	10.3	13.2	0.77
	Salmon	3,410	700	15.7	16.4	19.8	0.84
Connecticut	Hard	7,210	1155	12.9	13.5	16.2	0.82
	Salmon	4,670	770	18.6	19.1	21.8	0.87
Hudson Valley	Hard	4,740	745	14.0	14.6	17.7	0.80
	Salmon	2,580	425	19.5	20.0	24.3	0.83
New York, except Hudson Valley	Hard	4,770	1005	14.4	15.4	18.3	0.83
New Jersey	Hard	5,410	900	9.1	10.0	13.6	0.73
	Salmon	2,080	530	17.7	18.9	22.1	0.80
Delaware	Hard	8,040	1210	8.9	7.7	12.0	0.63
	Salmon	2,800	450	12.9	13.8	16.0	0.86
Baltimore, Md.	Hard	5,990	1330	8.0	9.1	12.3	0.75
	Salmon	3,130	645	17.3	18.2	20.9	0.88
Maryland, except Baltimore	Hard	4,440	960	8.4	9.2	13.4	0.68
	Salmon	2,680	570	14.1	15.4	18.5	0.83
Philadelphia, Pa.	Hard	6,580	855	8.[illegible]	9.8	14.5	0.67
	Salmon	2,520	355	16.7	17.9	22.9	0.79
Eastern Pennsylvania, except Philadelphia	Hard	8,080	1415	7.8	8.7	11.8	0.73
	Salmon	3,250	580	17.0	18.0	21.3	0.82
Pittsburgh, Pa.	Hard	11,060	2055	4.8	5.5	7.7	0.69
	Salmon	4,880	955	11.4	12.1	14.1	0.85
West Virginia and Western Pennsylvania, except Pittsburgh	Hard	11,450	1845	4.9	5.6	8.0	0.69
	Salmon	4,810	940	11.7	12.5	14.6	0.85
Cleveland, Ohio	Hard	9,820	1185	8.2	8.7	11.1	0.78
	Salmon	7,780	1285	9.7	10.3	12.0	0.85
Northern Ohio, except Cleveland	Hard	12,110	1720	7.1	7.9	10.4	0.68
	Salmon	3,910	620	12.6	13.5	14.6	0.79
Detroit, Mich.	Hard	4,330	900	15.6	16.5	19.5	0.81
	Salmon	2,540	555	18.9	19.4	20.8	0.93
Wisconsin	Hard	5,330	1110	15.6	16.6	20.3	0.81
	Salmon	2,320	470	24.4	25.2	28.0	0.90
Chicago, Ill.	Hard	3,450	1265	13.2	15.2	19.0	0.79
	Salmon	2,400	420	20.0	22.4	26.5	0.85
Illinois, except Chicago	Hard	13,050	1580	5.2	6.2	8.0	0.75
	Salmon	6,330	780	14.3	15.2	17.2	0.88
Kentucky	Hard	7,780	1255	10.3	11.2	15.5	0.73
	Salmon	4,010	720	14.7	15.8	19.0	0.84
Southern Indiana	Hard	16,280	2360	1.8	2.3	5.4	0.37
St. Louis, Mo.	Hard	11,040	1465	6.0	6.7	9.1	0.70
	Salmon	5,940	585	13.8	14.7	16.3	0.90
Missouri, except St. Louis	Hard	14,660	2020	2.9	3.8	5.7	0.61
	Salmon	6,430	1170	12.9	13.8	15.8	0.88
Nebraska	Hard	8,300	1025	8.7	9.7	13.3	0.73
	Salmon	2,480	460	14.0	15.3	20.6	0.76
Kansas	Hard	15,850	1915	3.2	3.8	5.1	0.59
	Salmon	4,500	600	15.2	16.0	17.6	0.91
Denver, Colorado	Hard	5,050	620	10.4	11.3	13.5	0.82
	Salmon	4,210	415	13.6	14.4	16.4	0.88
Colorado, except Denver	Hard	7,340	1145	10.3	11.1	13.3	0.83
	Salmon	4,900	740	15.5	16.0	17.8	0.90
Utah	Hard	7,490	1305	13.0	14.2	16.6	0.78
Wyoming	Hard	6,310	1410	7.2	8.1	12.1	0.68
	Salmon	5,680	300	13.4	13.9	16.3	0.85
Washington and Oregon	Hard	7,600	1245	9.5	10.3	14.1	0.70
	Salmon	3,240	580	15.9	17.0	20.1	0.85
Los Angeles, Calif.	Hard	3,690	600	11.2	11.8	14.2	0.83
California, except Los Angeles	Hard	4,640	735	11.0	12.7	15.2	0.84
Texas	Hard	7,285	1020	11.1	12.0	14.3	0.82
Mississippi, Louisiana and Arkansas	Hard	6,320	911	11.4	12.3	16.5	0.79
	Salmon	2,580	485	10.1	11.1	16.8	0.67
Alabama, Tennessee and North Carolina	Hard	9,700	1525	7.0	7.0	10.6	0.72
	Salmon	4,510	750	17.6	18.9	21.0	0.89
Richmond, Va.	Hard	9,350	1315	7.4	8.3	11.1	0.74
	Salmon	4,120	650	15.0	15.9	18.0	0.88
Virginia, except Richmond	Hard	9,470	1815	6.7	7.5	10.0	0.75
	Salmon	6,560	1440	11.2	11.9	13.8	0.87
Washington, D. C.	Hard	5,700	875	8.3	9.4	12.9	0.72
	Salmon	3,500	385	14.3	15.4	16.7	0.91
Weighted average of all samples, both hard and salmon		7,246	1154	10.12	10.92	13.99	0.764
Weighted average of all Hard Samples		7,434	1183	9.77	10.56	13.66	0.758
Weighted average of all Salmon Samples		4,094	678	15.94	16.77	19.41	0.851

tests were made at the Bureau of Standards by representatives of the Common Brick Manufacturers Association* using A.S.T.M. procedure (see Ser. Des. C67–31). Table 2 shows distribution of properties of hard bricks covered in this survey. The terms hard and salmon were applied

TABLE 2.—DISTRIBUTION OF PROPERTIES OF "HARD BRICKS" FROM ALL PARTS OF THE UNITED STATES (McBurney and Lovewell).

Compressive Strength, Flatwise		Modulus of Rupture		Water Absorption				Ratio, 48 hr. Cold to 5 hr. Boiling Water Absorption	
Range, lb. per sq. in.	Percentage of Production Within Range	Range, lb. per sq. in.	Percentage of Production Within Range	Range, per cent	Percentage of Production Within Range			Range	Percentage of Production Within Range
					5 hr. Cold	48 hr. Cold	5 hr. Boiling		
21,001 to 22,500	0.46	2101 to 3450	6.95	0 to 2.00	3.87	2.65	0.53	0.16 to 0.30	0.37
19,501 to 21,000	0.69	1951 to 2100	3.00	2.01 to 4.00	8.05	4.96	2.77	0.31 to 0.35	0.45
18,001 to 19,501	0.46	1801 to 1950	2.74	4.01 to 6.00	14.99	13.00	3.27	0.36 to 0.40	0.21
16,501 to 18,000	2.04	1651 to 1800	7.57	6.01 to 8.00	13.73	14.22	9.94	0.41 to 0.45	0.64
15,001 to 16,500	1.49	1501 to 1650	8.34	8.01 to 10.00	16.52	15.82	13.77	0.46 to 0.50	1.28
13,501 to 15,000	3.71	1351 to 1500	5.34	10.01 to 12.00	11.80	11.77	11.19	0.51 to 0.55	1.17
12,001 to 13,500	4.76	1201 to 1350	7.12	12.01 to 14.00	11.14	14.29	13.88	0.56 to 0.60	3.30
10,501 to 12,000	7.78	1051 to 1200	10.55	14.01 to 16.00	8.84	8.24	13.09	0.61 to 0.65	8.64
9,001 to 10,500	8.61	901 to 1050	10.44	16.01 to 18.00	5.01	5.52	11.02	0.66 to 0.70	12.37
7,501 to 9,000	11.92	751 to 900	13.60	18.01 to 20.00	2.42	4.77	9.14	0.71 to 0.75	16.80
6,001 to 7,500	15.47	601 to 750	11.74	20.01 to 22.00	2.22	2.31	5.72	0.76 to 0.80	19.41
4,501 to 6,000	16.81	451 to 600	7.52	22.01 to 24.00	1.31	0.64	2.14	0.81 to 0.85	15.65
3,001 to 4,500	17.97	301 to 450	4.35	24.01 to 26.00	0.00	0.68	1.95	0.86 to 0.90	13.89
1,501 to 3,000	7.46	151 to 300	0.37	26.01 to 28.00	0.11	0.00	0.75	0.91 to 0.95	5.32
0 to 1,500	0.36	0 to 150	0.37	28.01 to 34.00	0.00	0.11	0.75	0.96 to 1.00	0.51
Total per cent	99.99		100.00		100.01	99.98	99.91		100.01

TABLE 3.—EFFECT OF 51 CYCLES OF FREEZING AND THAWING ON INDIVIDUAL BRICKS CLASSIFIED ACCORDING TO FLAT COMPRESSIVE STRENGTH AND RATIO OF 48 HR. COLD TO 5 HR. BOILING WATER ABSORPTION (McBurney and Lovewell).

S = satisfactory. U = unsatisfactory (loss 3 per cent or more in weight). Figures show number of bricks.

Range, Compressive Strength, Flatwise, lb. per sq. in.	Range, ratio 48 hr. cold to 5 hr. boiling water absorption.																			
	0 to 0.40		0.40 to 0.60		0.60 to 0.70		0.70 to 0.75		0.75 to 0.80		0.80 to 0.85		0.85 to 0.90		0.90 to 0.95		0.95 to 1.00		Total No. Bricks	
	S	U	S	U	S	U	S	U	S	U	S	U	S	U	S	U	S	U	S	U
0 to 1,500	...	...	0	1*	4	3*	1	0	1	6	3	12	0	5	0	1	0	2	9	30
1,501 to 2,500	...	...	1	0	6	2*	1	0	9	7	10	13	6	15	2	7	0	2	35	46
2,501 to 3,500	...	...	1	0	2	0	1	0	3	0	11	9	18	39	4	14	1	3	41	65
3,501 to 4,500	...	...	1	0	...	...	3	1*	12	0	7	7	13	20	9	24	1	0	46	52
4,501 to 6,000	...	...	...	...	1	0	3	0	8	0	21	8	17	15	3	11	...	...	53	34
6,001 to 8,000	...	...	...	...	1	0	1	0	...	...	13	0	14	4	3	1	...	...	32	5
8,001 to 12,000	...	...	2	0	2	0	2	0	1	0	2	0	5	1	1	1	...	...	15	2
12,001 to 15,000	...	...	2	0	3	0	2	0	...	...	...	...	...	...	...	...	...	...	7	0
15,000+	2	0	5	0	2	0	...	...	...	...	...	...	...	...	...	...	...	...	9	0
Total	2	0	12	1	21	5	14	1	34	13	67	49	73	99	22	59	2	7	247	234

* From Hudson Valley.

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* Reported in *Proc. A.S.T.M.*, Vol. 33, Pt. 2, p. 636.

by the manufacturer and indicated brick which he estimated to be satisfactory and unsatisfactory in weathering resistance. Table 3 shows the effect of freezing and thawing on brick of doubtful weathering resistance.

These tests indicate that shale brick can be separated into resistant material by requiring either a compression strength not less than 7500 lb./in.^{2} or a modulus of rupture not less than 1200 lb./in.^{2} or an absorption after 5 hr. boil not more than 12 per cent. Bricks with compressive strengths of 4500 lb./in.^{2} or more, C/B ratios less than 0.8, or compressive strengths over 6000 lb./in.^{2} and C/B less than 0.85 appear satisfactory in resistance to freezing and thawing.

From a consideration of the existing data, the following grades and requirements are suggested for building bricks of *clay or shale:*

Grade	Compressive Strength (tested flatwise), lb. per sq. in.		Modulus of Rupture (flatwise on 7-in. span), lb. per sq. in.		Ratio of Absorptions* $\frac{C_{24}}{B_5}$	
	Mean of 5 Tests	Individual Minimum	Mean of 5 Tests	Individual Minimum	Mean of 5 Tests	Individual Maximum
A	4500 or over	3500	750 or over	550	0.75	0.80
B	2500–4500	2000	500 or over	350	0.80	0.85
C	1500–2500	1250	300 or over	200	No Limit	

* Requirement may be waived if brick are not exposed to freezing and thawing or where the compressive strength exceeds 8000 lb./in.^{2} and the absorption after 5 hr. boil is less than 8 per cent.

Grade A brick is suggested for use where strength and resistance to freezing and thawing in presence of moisture are required; grade B is suggested for use where lower strength is acceptable and where brick are not saturated when exposed to freezing and thawing; grade C is intended for back up or interior masonry, or for exteriors not exposed to freezing.

First quality sewer brick should show an average compressive strength of 8000 lb./in.^{2} or more, a modulus of rupture of 1000 lb./in.^{2} or more, a C_{24}/B_5 ratio of 0.75 or less, and an average absorption not over 6 per cent. For detailed specifications and methods of testing brick, see A.S.T.M. *Standards*.

From the average physical properties of the clay brick shown in Table 4 it will be observed that the ratios of the average tensile strength to the average modulus of rupture range between 30 and 40 per cent and that the ratio of the average punching shear strength to the average compressive strength flatwise varies from a third to a half.

Griffith also found that the approximate relationship between the crushing strength and absorption of stone (Art. 271) holds for brick and other structural silicates.

Fig. 6 shows stress-deformation curves for three grades of brick tested on end. The softer varieties of brick exhibit stress deformation curves of still sharper curvature. The modulus of elasticity of such brick generally lies between 1,500,000 and 2,000,000 lb. per sq. in.

301. Specific Gravity of Brick.—The bulk specific gravity of brick ranges from 1.6 to 2.5, depending upon the character of the raw materials and the degree of burning. Brick made from impure fire-clays generally have a lower specific gravity than those made from shales. For well-burned brick the bulk specific gravity will usually lie between 2.0 and 2.4. Specific gravity of pulverized building brick runs from 2.5 to 2.9.

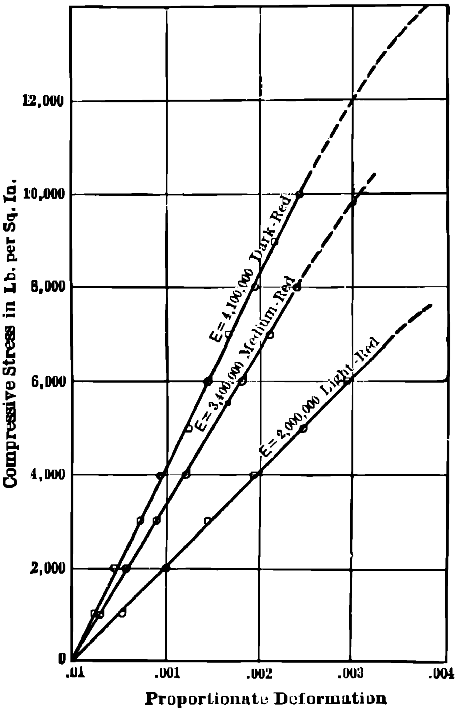

Fig. 6.

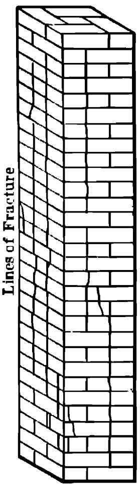

Fig. 7.

Fig. 6.—Elastic Properties of Common Brick Used in Pier Tests. The average crushing strength of these three grades of brick, crushed endwise, was 14,000, 10,500, and 7500 lb. per square inch, respectively. (*Tests of Metals*, 1885, p. 1138.)

Fig. 7.—Showing Method of Failure of Brick Piers. (*Tests of Metals*, 1883.)

302. Crushing Tests on Brick Masonry.—The main conditions governing the strength of brick masonry under concentric loading are: (1) the strength of brick, (2) the strength and elasticity of mortar, (3) quality of workmanship in laying, (4) method of laying, (5) regularity in form of brick. The stiffness of masonry is dependent largely upon the modulus of elasticity of the mortar, the quality of workmanship in laying, and the modulus of elasticity of the brick.

Fig. 7 shows the typical method of failure of brick columns. Transverse failure of individual brick usually begins at loads between 50 and 80 per cent of the maximum (Tables 5 and 6). The pier or wall then gradually separates into a number of slender columns and failure ensues.

TABLE 4.—AVERAGE PHYSICAL PROPERTIES OF BRICK USED IN WALLS OF TABLE 5

Locality Represented or Kind	Absorption		Strength in Pounds per Square Inch			
	5 hr. Boil	48 hr. Immersion	Modulus of Rupture Flatwise	Compression Flatwise	Tension	Punching Shear
Chicago............	16.5	11.7	1225	3280	417	1100[a]
Detroit.............	22.3	20.7	670	3540	222	1165[a]
Mississippi..........	21.7	16.7	820	3410	317	1590[a]
New England.......	9.2	6.9	1550	8600	601	3550[b]
Sand Lime..........	13.2	....	560	4150	210	1230[c]

Each average represents 50 tests except as noted: [a] represents 10 tests; [b] represents 4 tests; [c] represents 70 tests.

TABLE 5.—COMPRESSIVE STRENGTH OF BRICK WALLS *

Walls 8 and 12 in. thick, 6 ft. long, and 9 ft. high. Solid construction, common bond, headers every sixth course, joints ¼ to ½ in. thick. Workmanship *A*, beds furrowed vertical joints not filled; *B*, beds well spread and vertical joints filled.

Workmanship	No. Walls Tested	Mortar Mix by Vol. C : L : S	Compressive Strengths, lb./in.^{2}				Secant Modulus of Elasticity in 1,000 lb./in.^{2}	Average Ratios		
			Brick Flatwise (*B*)	Mortar 2×4-in. Cylinders (*M*)	Walls			$\frac{W}{B}$	$\frac{W}{M}$	Load at First Crack to Max. Load
					Av. (*W*)	Min.				
B	5	**1 : 0.1 : 3**	3280	3260	905	755	1300	0.28	0.28	0.94
	6	....	3540	....	1145	895	830	0.32	0.35	0.89
	6	....	3410	....	1510	1335	1420	0.44	0.46	0.88
	6	....	8600	....	2710	2040	2500	0.31	0.83	0.75
B	6	1 : 1 : 6	3540	1100	945	760	680	0.27	0.86	0.59
	6	....	3410	....	1230	965	1160	0.36	1.10	0.92
	6	....	8600	....	1840	1710	2260	0.21	1.65	0.62
A	5	1 : 0 : 3	3280	3580	660	580	620	0.20	0.18	0.94
	6	....	4150†	....	905	800	1300	0.22	0.25	0.77
A	6	1 : 1¼ : 6	3280	1070	585	575	510	0.18	0.55	0.98
	6	....	4150†	....	625	550	740	0.15	0.58	0.80
A	6	0 : 1¼ : 3	3280	90	285	250	62	0.09	3.15	0.71
	6	....	4150†	....	300	280	93	0.07	3.35	0.69

* Data from U. S. Bureau of Standards, *RP108*, and *Tech. Paper* No. 276.
† Sand lime brick.

Because of differences in ratio of height to least width, a homogeneous pier or wall having a height to width ratio between 6 : 1 and 10 : 1 should have only 70 per cent of the crushing strength of a brick tested flatwise.

Owing to mortar joints, strength and elastic properties of masonry never reach this ratio. The data by Stang, Parsons, and McBurney given in Table 5 and those of Talbot in Table 6 show that the strengths of walls and piers made from ordinary bricks and mortars usually run between 0.1 and 0.4 of the compressive strength of the component brick tested flatwise.

TABLE 6.—AVERAGE RESULTS OF COMPRESSIVE TESTS ON BRICK COLUMNS

[See *Bulletin* No. 27, Engr. Expt. Sta., Univ. of Ill.]

Columns were $12\frac{1}{2} \times 12\frac{1}{2}$ in. × 10 ft. and consisted of 40 to 43 courses of brick laid with $\frac{3}{8}$-in. joints.

No. of Tests.	Characteristics of Columns.			Average Ultimate Strength Lb./In.^{2}†	Proportion of Load at which Popping Occurred.‡	Ratio of Strength of Columns to Strength of			Modulus of Elasticity in 1000 Lb./In.^{2}
	How Laid.	Mix of Mortar.*	Age Days.			Brick	First Set.	6-in. Mortar Cubes.	
				SHALE BUILDING BRICK					
3	Well	1 P : 3S	67	3365	.56	.31	1.00	1.17	4783
2	Well	1 P : 3S	181	3950	......	.37	1.18	.....	5025
2	Well	1 P : 3S	68	2800[1]	.66	.26	.83	.....	4400
2	Poorly	1 P : 3S	67	2920	.62	.27	.87	1.05	3525
2	Well	1 P : 5S	65	2225	.52	.21	.66	1.30	3250
1	Well	1 N : 3S	67	1750	.40	.16	.52	5.75	800
2	Well	1 L : 2S	66	1450	.43	.14	.43	.....	104
				UNDERBURNED CLAY BRICK					
2	Well	1 P : 3S	63	1060	.76	.27	.31	.37	433

* P = Portland cement; S = sand; N = natural cement; L = lime.

† The maximum range in strength for any set of columns was less than 13 per cent.

‡ Popping was probably due to transverse rupture of brick.

[1] These columns were loaded with 1-inch eccentricity.

Supporting evidence on the influence of the strength of the component brick is afforded by the tests reported by Bragg in *Technologic Paper* No. III. These tests were made at the Bureau of Standards on large piers 30 in. by 30 in. by 10 ft., built of four grades of brick ranging in crushing strength from 1600 to 12,000 lb./in.^{2}, with three mortars. They indicate that the strengths of piers can be raised by increasing the depths of the units or by breaking joints every few courses rather than every course. These tests and others at Watertown Arsenal also show that a decided advantage in masonry strength obtains when brick are laid on edge. Insertion of wire mesh in every horizontal joint also caused a small increase in strength. As a result of these tests, Bragg proposed the expression

$P=Kp$, where $P=$ unit crushing strength of pier, $p=$ unit compressive strength of brick, and K is a constant depending on the mortar. For brick laid flatwise in 1 : 3 Portland cement mortar, he suggested $K=0.27$, and for 1 : 6 lime mortar, $K=0.11$.

Tests made at the Watertown Arsenal * clearly show the advantage of using mortar stronger than a 1 : 3 mix with very hard burned brick. In tests of piers of wire-cut brick having a crushing strength of approximately 13,000 lb. per square inch, those laid in neat Portland cement had a strength of 31 per cent of the brick, whereas those laid in 1 : 3 Portland cement mortar possessed only 19 per cent of the strength of the brick.

The advantage of stiffness arising from the use of strong mortar in the joints is also well illustrated in the data of Tables 5 and 6.

The data in Table 5 and other evidence from the Stang, Parsons, and McBurney tests show that increases of 30 to 100 per cent in the crushing strength and material gains in stiffness of brick masonry can be realized if the *mortar* is spread on *horizontal joints* and *filled into vertical joints* rather than grooved on the beds and omitted from the vertical joints.

The existing data indicate that the crushing strength of well-laid brick masonry varies directly with the crushing strength of the brick and roughly with the cube root of the compressive strength of the mortar.

303. Resistance of Brick Walls to Fire.—In a series of fire tests on 6×9-ft. wall panels at the Underwriters' Laboratories, in Chicago, brick panels showed marked resistance to fire and low conductivity. Tests were made on a 12-in. wall of well-burned Chicago brick, an 8-in. panel of hydraulic-pressed brick from Indiana, an 8-in. panel of common brick from St. Louis, and an 8-in. panel of sand-lime brick from Indiana. The strengths and absorptive properties of these bricks are given in Table 7. With the exception of the panel made of hydraulic brick which was laid in lime putty, cement mortar was used. The tests were made by subjecting the face of the panel to a temperature which rose to about 800° C. in one-half hour and then varied between 800 and 900° C. for one and one-half hours, at which time the panel was removed and the face quenched by water from a fire-hose. Each high temperature recorded in Table 7 represents an average of a number of pyrometer readings, the thermo-couples being arranged to secure the variation in temperature at different parts of the furnace and at various points on the face of the wall.

The panels of clay brick withstood the tests better than the panel of sand-lime brick. The panel of hydraulic-pressed brick was in the most perfect condition after quenching. About 18 per cent of the brick on the face of this panel were cracked through and a very few were spalled. The Chicago brick contained lime knots which caused a large percentage of the exposed brick to crack when quenched. In 60 to 70 per cent of these the

* *Tests of Metals*, 1904.

TABLE 7.—EFFECTS OF HIGH TEMPERATURE ON BRICK AND BRICK WALLS

[*Bulletin* No. 370 U. S. Geological Survey.]

Wall panels fired for two hours, for one hour at maximum temperature.

Kind of Brick.	Common Clay.	Hard-burned Clay.	Hyd-pressed Brick.	Sand-Lime.
Thickness of panel, in.	8	12	8	8
Maximum average temperature on exposed face in ° C.	850	770	850	790
Maximum average temperature on unexposed face after 2 hr. in ° C.	58	18	35	55
Mean temperature of air on unexposed face.	23	3	3	19
No. unexposed brick tested transversely.	5	2	2	5
Average modulus of rupture of unexposed brick, lb./in.^{2}	1178	482	718	319
No. exposed brick tested transversely.	0	0	0	5
Average modulus of rupture of exposed brick, lb./in.^{2}	......	......	......	56
No. unexposed brick crushed.	5	13	13	5
Average crushing strength of unexposed brick, lb./in.^{2}	3866	2729	4440	2035
No. exposed brick crushed.	0	13	13	5
Average crushing strength of exposed brick, lb./in.^{2}	......	2793	3701	1750
No. unexposed * brick immersed.	5	2	2	5
Average per cent absorption, unexposed brick, after forty-eight hours' immersion.	6.2	20.2	10.7	15.9

* Absorptions of exposed brick were about the same as for unexposed brick.

cracks were sufficiently large to permit picking off portions of the brick. About half of the faces of the St. Louis brick were so cracked at the conclusion of the test that they could be readily removed, and the face of the wall was discolored to a depth of about 1 in. After firing, the face of the panel ot sand-lime brick looked soft and chalky. It was washed away to a depth of $\frac{3}{8}$ to $\frac{3}{4}$ in. when the hose was applied. Only about 20 per cent of the exposed brick could be removed from the wall intact.

SAND-LIME BRICK *

Although not a clay product, the fact that a million dollars' worth of sand-lime brick are annually used as a substitute for clay brick warrants a brief discussion of their manufacture and properties in this chapter.

304. Definition.—Sand-lime bricks are made from a lean mixture of slaked lime and fine silicious sand, molded under mechanical pressure and hardened under steam pressure.

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* For further information on sand-lime brick see *Cements, Limes and Plasters*, by E. C. Eckel. An interesting article on *The Chemistry of Sand-lime Brick*, by T. R. Ernest appears in *Trans. Am. Ceramic Society*, Vol. 13, p. 649.

305. Manufacture.—The sand should be free from clay or mica. It should all pass a 20-mesh and three-fourths of it should be retained on 100-mesh. If the grains run larger than a 20-mesh, the coarse particles must be screened out or reduced in a tube-mill. A high-calcium lime is preferred to a brown or dolomitic lime owing to the rapidity with which the former hardens. The requisite percentage of lime varies between 4 and 10 per cent. Generally the lime is slaked before mixing with the sand by placing it beneath the brick cars in the hardening cylinder and allowing the steam to act upon it. Often the sand and lime are mixed dry in a tube-mill and the mixture is then tempered in a special type of pug-mill. In some plants the quick-lime is slaked, the sand ground, and an intimate mixture secured by running the wet sand and lime through a wet and dry grinding mill, an apparatus similar to a dry-pan. Molding is done in powerful presses, some of which can exert a compression of 20,000 lb. per square inch on the surface of the brick. After removal from the press the brick are stacked on cars which are run into the hardening cylinders. In the latter a steam pressure of 100 to 150 lb. per square inch is used. After hardening for six to ten hours the brick are ready for use.

306. Comparison of Clay and Sand-lime Brick.—On account of their smooth surfaces, even shape, freedom from efflorescence, uniform color and satisfactory strength, sand-lime brick are sometimes preferred to clay brick. Some of the American sand-lime brick, however, have not been as durable when exposed to the weather as good grades of clay brick. Unless made with great care sand-lime brick do not resist frost action or fire as well as clay brick.

307. Physical Properties of Sand-lime Brick.—Good sand-lime brick bedded flatwise have a compressive strength between 2500 and 5000 lb. per square inch. In cross-bending the modulus of rupture should exceed 450 lb. per square inch. After boiling 5 hours good brick should not show more than 18 per cent absorption. The bulk specific gravity commonly lies between 1.8 and 2.0.

PAVING BRICK *

308. Manufacture.—Paving brick are made from three classes of clay: surface clays, impure fire-clays, and shale. Owing to the narrowness of the vitrification range for most surface clays, they are apt to produce either underburned or overburned brick. Impure fire-clays make a good

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*Additional information on methods of manufacture may be gotten from *Vitrified Paving Brick*, by H. A. Wheeler, Randall & Co.; and from *Burning Brick in Down-draft Kilns*, by W. D. Richardson, Randall & Co.

brick when sufficiently vitrified, but require a high temperature. The shales are by far the best source of raw material for paving brick. Wheeler suggests that shales suitable for paving brick should approximate the following analysis: silica (SiO_2) = 56, alumina (Al_2O_3) = 22, ignition loss = 7, lime (CaO) = 1, magnesia (MgO) = 1, alkalies (K_2O and Na_2O) = 4 per cent. Fluxing impurities in the above analysis total 13 per cent.

Approximately three-fourths of the paving brick produced in this country are vertical fiber lug brick made in 3 standard depths $2\frac{1}{2} \pm \frac{1}{8}$, $3 \pm \frac{1}{8}$, and $3\frac{1}{2} \pm \frac{1}{8}$ in., with a width of $4 \pm \frac{1}{8}$ in. and length of $8\frac{1}{2} \pm \frac{1}{4}$ in. Of these sizes the 3-in. depth is the most used. These brick have plain wire-cut faces with two or more lugs on one side and a vertical bar lug or lugs on each end. Lugs extend from $\frac{1}{8}$ to $\frac{1}{4}$ in. beyond the body dimensions mentioned above. A small proportion of the older re-pressed lug variety with four lugs on one side, still standard in the $3\frac{1}{2} \pm \frac{1}{8}$ by $4 \pm \frac{1}{8}$ by $8\frac{1}{2} \pm \frac{1}{4}$ in. size, is also marketed.

De-airing has been introduced in molding paving brick with accompanying improvements in density, strength, and resistance to abrasion.

Paving brick are generally burned in down-draft or continuous kilns. From seven to ten days are required in burning and a like period for proper annealing. The temperature required to bring shales to complete vitrification (Wheeler) is 850 to 1100° C. Impure fire-clays require a temperature from 100 to 200° C. higher.

By employing impure fire-clay, with which danger of over-burning is small, as high as 90 per cent of first-class paving brick may be produced. Using shale it is not possible to average more than 75 per cent of first-class pavers.

309. Requirements of Good Paving Brick.—Every brick should be free from marked distortion, should have one plane face, and should be free from cracks, checks, blisters, and kiln marks over $\frac{3}{16}$ in. deep. It should give a high metallic ring when struck with a hammer and should, when broken, exhibit a uniform close-grained structure free from laminations. The interior of a properly burned brick cannot be scratched with a knife. *Uniformity in quality is of vital importance in order that the pavement may wear evenly.*

310. Physical Properties of Paving Brick.—Good brick should have a crushing strength in excess of 8000 lb. per square inch. The transverse strength (modulus of rupture) should not be less than 1500 lb. per square inch. Low transverse strength may be due to either overburning or improper annealing. After immersion 24 hr. in water at room temperature, shale brick when properly vitrified generally absorb between 0.5 and 2 per cent; brick made of impure fire-clay may absorb as high as 5 per cent. An absorption less than 0.5 per cent generally denotes over-burning. In bulk specific gravity, shale pavers commonly range between 2.2 and 2.5, impure fire-clay between 2.1 and 2.3. The better grades of paving brick lose less than 20 per cent by weight, in the rattler test. Wide variation in the losses of individual brick indicate non-uniformity in methods of manufacture and are sufficient cause for rejection of brick even though the average loss is small.

REFRACTORY BRICK *

311. Introduction.—Certain classes of brick are much employed to line flues, hearths and the various classes of furnaces used in metallurgical processes. Such brick must be able to withstand high temperatures without undue softening or change in volume, must resist the action of gases and slags generated during the process, must resist abrasion when hot, and must possess low thermal conductivity. In accordance with the character of the chemical reaction which different refractory brick resist, they are divided into three classes: acid, basic and neutral.

312. Acid Brick.—The brick which are commonly used to resist the action of silicious and other acid slags are fire-brick and silica brick.

Fire-brick are made from fire-clays which are sometimes grogged with small percentages of sand to reduce shrinkage. The clay generally consists of $\frac{1}{2}$ to $\frac{3}{4}$ silica, $\frac{1}{5}$ to $\frac{2}{5}$ alumina and less than 10 per cent of fluxes. The more refractory brick are made from clays having low flux contents and high alumina contents. A very high alumina content, however, gives the brick a basic reaction. The brick are molded by either the soft- or stiff-mud processes and repressed after partial drying.

First class fire-brick should have a modulus of rupture of at least 500 lb. per square inch and should withstand a load of 25 lb. per square inch at a temperature of 1350° C. without deforming over 6 per cent. They should not soften at a temperature less than 1700° C.†

313. Silica Brick.—Quartzite, sandstone, or silica sand, which consists of 95 per cent or more pure silica, are the main constituents used in making silica brick. If the silicious rock contains small percentages of clay it is sometimes possible to mold the brick without artificial additions. The English ganister brick is made from such material. Ordinarily, however, the ground silicious rock or the sand are not sufficiently plastic when tempered with water and are adulterated either with very small percentages of fire-clay or about $1\frac{1}{2}$ per cent of high-calcium lime. Silica brick are burned at temperatures slightly higher than fire-brick.

On account of their brittleness and expansibility when heated, silica brick must be laid with wide joints. The compressive strength of silica brick tested flatwise often exceeds 2000 lb. per square inch. The softening temperature ranges from 1700 to 1800° C.

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* For additional information on refractory materials reference should be made to Havard's *Refractories and Furnaces*, from which considerable of this material has been drawn.

† See *Technologic Paper* No. 7, U. S. Bureau of Standards.

314. Basic Brick.—For lining basic Bessemer converters, basic open-hearth furnaces, blast furnaces, copper furnaces and other vessels subjected to the action of basic slags, magnesia brick are quite generally used. Magnesia brick are made from magnesite, nearly pure magnesium carbonate, of which the most satisfactory supplies are found in Greece and in Styria, an Austrian province. The magnesite is first calcined at 800° C., a temperature which is sufficient to free the carbon dioxide. This preliminary calcination of Grecian magnesite is generally done at the mines. At the brick plant a large proportion of the calcined product is sintered at a temperature of 1800° C. It is then mixed with 1 to 50 per cent of calcined magnesia and the mass is tempered with a small proportion of water. For brick which must resist high temperatures the proportion of calcined magnesia must be low. Since such mixtures are of low plasticity a very little tar or magnesium chloride is sometimes added for a binder. The brick are then hand-molded partially dried and repressed. After further drying, the brick, which have very little tenacity, are carefully stacked in a double layer in a down-draft kiln and burned.

Styrian magnesite is sorted, dead-burned, and again freed from impurities. The sintered magnesia is then ground, tempered with a small proportion of water and molded into brick which are burned at a temperature above 1700° C. Brick made from Styrian magnesite are considered more refractory than others. Their softening temperature is approximately 2000° C.

Although not so satisfactory as magnesia, calcined dolomite, the double carbonate of magnesia and lime, is often used to make refractory brick. The natural rock or a mixture of the rock and clay is ground, tempered with water and molded into shape. After drying these are burned like magnesia brick. Dolomite brick suffer greater contraction at high temperatures than do magnesia brick.

In making bauxite bricks, the bauxite which consists of 50 per cent or more of alumina, with water, iron oxide, and silica for principal impurities is calcined and crushed to a fine powder. It is then mixed with 15 to 30 per cent of fire clay, tempered with water and molded into bricks. Although properly burned bauxite bricks are highly refractory, they have such a large shrinkage when heated to high temperatures that they have not come into general use. In experiments by Kanolt * on eight samples of brick the melting points varied from 1565 to 1785° C.

315. Neutral Brick.—At the slag line in a basic furnace and in certain ports, and flues where the reaction of the surrounding medium may be either acid or basic, refractory brick which are neutral in reaction are used.

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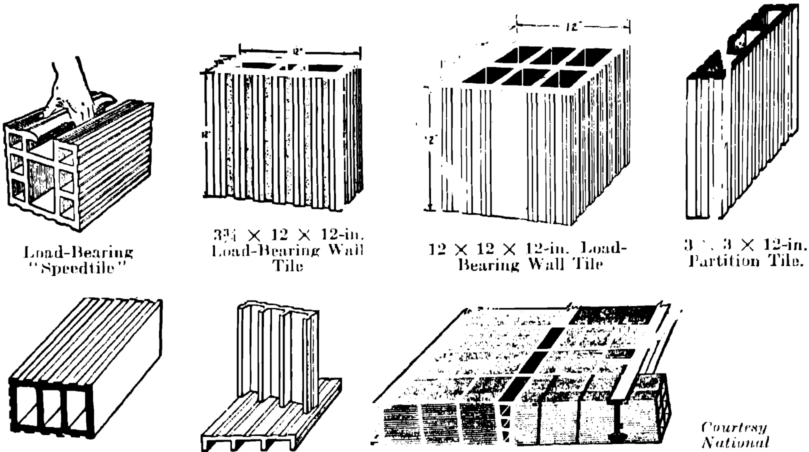
* *Technologic Paper* No. 10, U. S. Bureau of Standards.

Chromite, the oxide of iron and chromium, is the principal raw material used for making neutral refractory brick. The ore is crushed and mixed either with fire-clay or with magnesia and tempered with water in a wet-pan. The brick are molded, dried, and burned in much the same way as magnesia brick. Ordinarily the brick contain from 30 to 40 per cent chrome (Cr_2O_3), with alumina, iron oxide, magnesia, and silica in varying amounts. Chrome brick, although very resistant chemically to the action of slags and gases, are less refractory and weaker than magnesia brick. One sample tested by Kanolt had a melting-point of 2050° C.

BUILDING TILE

316. Wall Tile, Partition Tile, and Fireproofing.—For manufacturing wall tile, structural floor tile, partition tile, and fireproofing, plastic clays



Load-Bearing "Speedtile"

3¾ × 12 × 12-in. Load-Bearing Wall Tile

12 × 12 × 12-in. Load-Bearing Wall Tile

3 × 12 × 12-in. Partition Tile.

3 × 5 × 12-in. Backup Tile.

Furring Tile.

Flat Arch Floor Tile.

Courtesy National Fireproofing Corporation

FIG. 8.—Types of Clay Building Tile.

or shales mixed with clay are used. They burn to a hard, dense structure at a fairly low temperature, generally between 1100° and 1300° C. These forms are molded in machines of the auger or plunger type and are commonly burned in down-draft or continuous kilns. Fig. 8 shows typical shapes of these four classes of building tile. Most of such forms contain 45 to 55 per cent of air space or voids. Sections so made are sometimes inaccurately called terra-cotta blocks. Hollow blocks, frequently termed load-bearing tile, are used in load-bearing walls and partitions. For unplastered outside walls they are often salt-glazed. For walls which are to be plastered, blocks, tile, and fireproofing are often scored in order to furnish a better bond for the plaster. Load-bearing tile and structural floor tile are harder to burn and stronger than partition tile. The latter are used principally for partitions which carry no superimposed load. Fireproofing differs from partition tile chiefly in shape and size.

The advantages of hollow block and fireproofing are lightness, low permeability to water, low heat conductivity, and a rough surface to which plaster may be directly applied, thus avoiding the necessity of furring and lathing. Fire tests have shown, however, that partition tile and hollow blocks are likely to split at the junctions of webs and faces, especially when the hose is turned upon hot partitions.* It is, therefore, safe practice to insist on fire tests of hollow block panels when they are to be used for fire protection.

Load-bearing wall tile of good quality should be true in shape and dimensions. They should have a compressive strength when loaded on the sides in excess of 700 lb./in.^{2} of gross area and double that value when loaded on the ends. The better grades of wall tile exhibit strengths of two to three times these amounts. After boiling for 1 hr., good wall tile for service exposed to the weather should show less than 16 per cent absorption.

Structural clay load-bearing floor tile for arch construction, when loaded on sides should exhibit compressive strengths in excess of 1600 lb./in.^{2} of net area and double that amount when loaded on the ends.

The variability of wall tile and the necessity for testing them are shown by a large series of tests reported in *Proc. A.S.T.M.*, Vol. 17, Pt. 1, p. 334. Tile were selected by manufacturers to represent their product fairly. The compressive strengths in these tests ranged from 95 lb./in.^{2} of gross area, for a soft-burned tile loaded flatwise, to 6000 lb./in.^{2} for a medium-burned tile tested on end. Absorption, by weight, after boiling 5 hr., ranged from 1.8 per cent for a hard-burned specimen to 20.3 per cent for a very soft tile.

317. Tests of Pilasters and Hollow Block Columns.—Crushing tests on 16 pilasters between 12 by 12 and 20 by 24 in. in cross-section, laid in 1L : 1C : 4S mortar and loaded to duplicate structural conditions, were made by Shank at Ohio State University in 1936 (see Expt. Sta. *Bull.* No. 57). On pilasters made of common forms of load-bearing tile faced and capped with Detroit common brick the range in strength based on gross area was 489 to 805 lb./in.^{2}, average 550 lb./in.^{2}. For pilasters of Detroit common brick the values ranged from 802 to 928 and averaged 864 lb./in.^{2}.

In *Bull.* No. 27, Engr. Expt. Sta., University of Illinois, Talbot reports two series of test on columns made of hollow blocks 8 in. high, 4 in. wide, and 8 in. long, containing about 15 per cent of cell space. The blocks were laid in Portland cement mortar. Their compressive strengths varied between 3350 and 9070, averaging 5451 lb./in.^{2} of net cross-section.

The seven columns tested in 1907 were approximately 12 ft. high; the twelve columns of the 1908 series were 10 ft. high. Columns of the earlier series ranged in cross-section from $8\frac{1}{2}\times 8\frac{1}{2}$ in. to $17\frac{1}{2}\times 17\frac{1}{2}$ in.; all the columns of the later series were $12\frac{1}{2}\times 12\frac{1}{2}$ in. in cross-section. The columns of the earlier series were laid in 1 : 2 mortar. Most of the columns of the series of 1908 were laid in 1 : 3 mortar. The strengths of the columns tested in 1907 varied from 2710 to 3440 lb. per square inch; those tested in 1908 had strengths ranging from 3040 to 4300 lb. per square inch, the latter value being estimated. By reference to Art. 302 it will be noted that the strengths of these hollow block columns compare very favorably with the strengths of first-class brick columns. The initial modulus of elasticity of the columns varied between 1,910,000 and 2,860,000 lb. per square inch.

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* *Bulletin* 370, U. S. Geol. Survey.

318. Roofing Tile.—For making roofing tile, the clay must not only be plastic, but it must dry and burn without suffering distortion. Considerable care is also required in preparing the raw material. After being ground in a dry-pan and finely screened the clay is pugged in a wet-pan and made into balls which are stored in bins until wanted. The balls a[illegible] then taken to an auge[illegible]hine and molded int[illegible] tile [illegible] interlocking til[illegible] are [illegible] made, they [illegible] are formed the[illegible]ts. The vio[illegible] clots are [illegible] press[illegible]d into sub[illegible] tile on a [illegible]

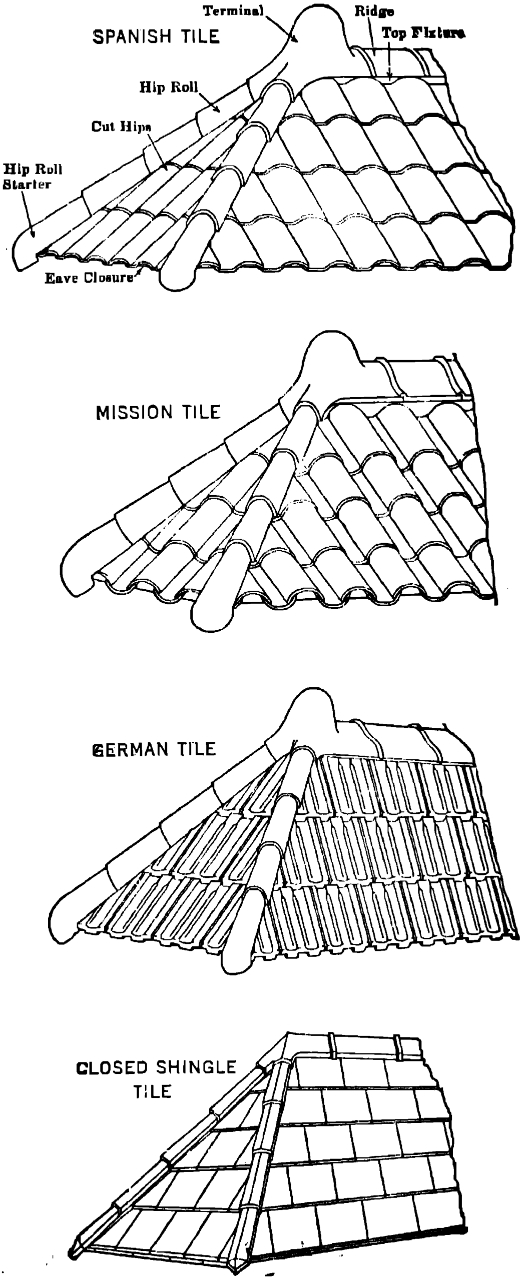

FIG. 9.—Examples of Various Roofing Tiles.

types of tile are shown in Fig. 9. After drying, roofing tile are burnt in saggers in down-draft kilns. Tile which are to serve as insulation against heat are soft-burned and porous. Where tile are to be subjected to freezing they are burned harder or glazed.

Roofing tile should be strong, durable, free from soluble salts, and impervious to water. Roofing tile, when properly made, form a strong, durable, fireproof roof which is a poor conductor of heat. The chief objections to tile roofing are the expense and the heaviness of the construction.

319. Floor-tile.—White-burning and red-burning clays, fire-clays and shales are used in making tile for floor surfaces. The chief considerations are color when burned, freedom from soluble salts, and absence of distortion and checking in burning. The dry-press process is used in molding, and down-draft kilns in burning.

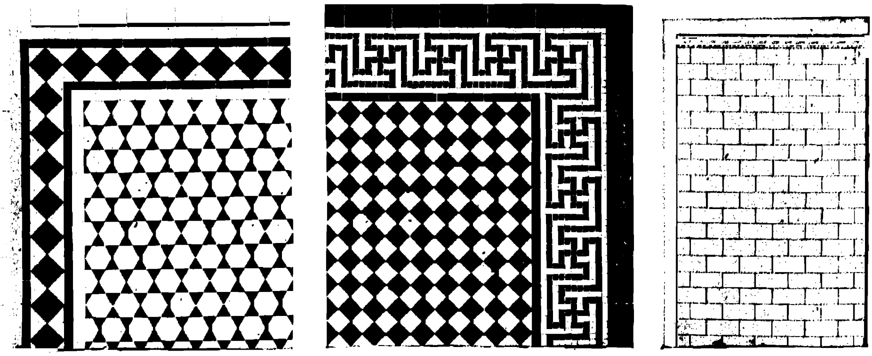
(a) (b) (c)

FIG. 10.—Floor Tile and Wall Tile Designs. (a) and (b) floor tile, (c) wall tile.

Floor-tile may be divided into two classes in accordance with the method of molding the design into the tile. They are face-tile, commonly called encaustic tile because they have a burnt-in design, and plain tile.

Plain tile are composed of the same clay or mixture of clay throughout. Frequently these are made in the form of mosaics. They may be either vitreous or semi-vitreous.

Plain face-tile are made by covering the die forming the base of the mold with a thin layer of specially prepared clay, filling the mold with a clay backing and compacting in a hand press. In making inlaid face-tile a cellular frame is placed on the bottom of the mold, and clays which have been properly colored are screened into the cells in accordance with the pattern scheme. The frame is then removed, the backing inserted, and pressure applied to compact the tile.

Floor-tile should show little absorption, have a high transverse strength and a high resistance to abrasion.

320. Wall-tile.—Tile for surfaces of walls differ from floor-tile principally in design and degree of burning. Wall-tile are burned at a comparatively low temperature, glazed, and fired again in a muffle-kiln at a still lower temperature. Wide difference in color, in shades of a single color, and in relief design can be obtained. Wall-tile are much used in wainscotings and to some extent in arches and ceilings. Floor and wall-tile designs appear in Fig. 10.

TERRA COTTA

321. Terra Cotta.—For the ornamentation of buildings and structures decorative terra cotta is widely used. It is less costly than stone when a number of pieces of a given pattern are frequently repeated in a structure. This economic advantage is especially worthy of consideration when the repeated patterns are of intricate design. The material weathers well and because of its glazed surface can be cleaned more easily than a porous stone.

Terra cotta is made from a finely ground mixture of fire-clay and shale, or fire-clay and impure clay, which is adulterated with ground brick or other burnt-clay product to reduce shrinkage. Plain forms of uniform section are extruded through dies; other simple shapes are hand-molded in plaster molds. Intricate patterns are modeled in green clay by sculptors and used for making plaster molds. Thirty to fifty pieces can be reproduced from a given mold. After being molded, terra-cotta parts are slowly dried to avoid checking and warping. They are then sprayed with a slip to impart the desired color to the goods on burning. To some parts glazes of bright or dull finish are also applied. Burning is done in muffle kilns or in continuous tunnel kilns. In the latter a period of about five days is required to burn the product. The maximum temperatures attained are about 1100 to 1200° C. To avoid kiln marks each piece is independently supported on fire-clay tile. After burning, rough edges are removed and parts are assembled and ground to fit.

CLAY PIPE

322. Sewer Pipe.—In the construction of sewers clay pipe has long been successfully used. S[illegible]er pipe must have high strength in order that it may carry the ditch f[illegible] To successfully withstand the action of acids and gases in the s[illegible] he pipe must be hard-burned and impervious. They should b[illegible] straight, smooth on the interior, and substantially free fr[illegible]les, and laminations.

[illegible] the maximum absorptior

Sewer pipe is made from red-burning clays, fire-clays, shales, and mixtures of shale and fire-clay. It is generally molded in vertical double-cylinder presses from a stiff-mud mix, although some pipe is made by the dry-press process. Sewer pipe is commonly burned in down-draft kilns at temperatures between 1050° and 1300° C. The term vitrified pipe is often a misnomer, since the burning temperature frequently is insufficient for vitrification. However, the firing should be carried to the stage of incipient vitrification. Salt glazing is generally practiced to insure a smooth and impervious surface. The pipe is made in lengths of about 3 ft. and in diameters up to 42 in. Sewer pipe are commonly provided with a bell on one end, into which the small end of an adjacent pipe is fitted. Joints are filled with 1 : 1 Portland cement mortar.*

In general, small fragments from good pipe will have an absorption less than 7 per cent after boiling 5 hr. in distilled water. Results of crushing tests in which the lower portion of the pipe was bedded in sand and the load applied on the top through a hardwood strip 1-in. wide appear in Table 8.

TABLE 8.—CRUSHING TESTS ON SEWER PIPE MADE BY THE MUNICIPAL SEWER-PIPE TESTING LABORATORY OF BROOKLYN, N. Y., IN 1909

[See *Municipal Journal*, Vol. 38, p. 160.]

Size of Pipe, In.	Total Number Tested.	Number Tested to Destruction.	Crushing Strengths in Pounds per Linear Foot of Pipe.			Required Strength, Lb. per Ft.†	Percentage of Failures.
			Maximum.	Minimum.	Average.		
6	170	169	2333	1033	1537	1000	0
12	245	245	2900	933	1542	1150	2.04
15	72	72	2800	1300	1935	1300	0
18	25	25	3100	1734	2389	1450	0
24	17	14	3800	2200	2825	2000	0
30	2	2	3280	3240	3260	....	0
30*	2	2	3240	3080	3160	....	0

* Double strength pipe. † Local standard.

323. Drain Tile.—Clay drain tile are made principally from shales and impure clays. The smaller sizes are molded in auger machines, but the larger ones are made in sewer-pipe presses. The tile are burned in a variety of kilns sometimes with brick or fireproofing. Kiln temperatures are lower than those used in burning sewer pipe, although the better grades of tile are burned until steel-hard. Salt-glazing is sometimes employed. Drain tile are generally cylindrical in [illegible] laid with uncemented butt joints through which the drainage [illegible]

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* The remarks in Art. 309 concerning [illegible] lness, texture, ring under the hammer of paving brick apply [illegible] and the better grades of drain tile.

Drain tile and sewer pipe should conform to the strength requirements tabulated below. These values are the same as the crushing loads per foot of length under sand bearings (see Art. 293). For relation of load to strength requirements for other bearings see A.S.T.M. Specifications.

AVERAGE STRENGTH REQUIREMENTS FOR CLAY AND CEMENT DRAIN TILE AND SEWER PIPE (From A.S.T.M. *Standards*, 1936)

Drain Tile				Sewer Pipe	
Internal Diameter of Tile, In.	Minimum Average Ordinary Supporting Strength in Pounds per Linear Foot for			Internal Diameter of Pipe, In.	Minimum Crushing Strength in Pounds per Linear Foot
	Farm Drain Tile (*a*)	Standard Drain Tile (*b*)	Extra-Quality Drain Tile (*c*)		
4	800	1200	1600	4	1430
5	800	1200	1600		
6	800	1200	1600	6	1430
8	800	1200	1600	8	1430
10	800	1200	1600	10	1570
12	800	1200	1600	12	1710
....	....	....	....	15	1960
15	1000	1300	1600	18	2375*
18	....	1400	1800	21	2850*
21	....	1550	2100	24	3425*
....	....	....	....	27	3950*
24	....	1700	2400	30	4525*
....	....	....	....	33	5050*
27	....	1850	2700	36	5575*
30	....	2000	3000		
33	....	2150	3300		
36	....	2300	3600	**A.S.T.M.*	
39	....	2450	3900	*Tent. Std.*,	
42	....	2600	4200	1938.	

(*a*) Farm drain tile for ordinary private drainage work on farms where the depth and size are moderate.

(*b*) Standard drain tile is for district drainage at moderate depths.

(*c*) Extra-quality drain tile is for district drainage where the depth is large and a first class pipe is needed.

Three methods of testing tile are outlined in Art. 293.

The maximum absorptions permitted by A.S.T.M. specifications for the three classes of drain tile are:

Kind of Tile	Maximum Percentage of Absorption		Permitted in Extra Quality
	Farm	Standard	
Shale and fire clay..........	11	9	7
Surface clay................	14	13	11
Concrete....................	12	10	9

For sewer pipe the maximum absorption should not exceed 8 per cent.

324. Conduit.—In large cities considerable use is now made of clay conduits for carrying underground cables and wires. Hollow rectangular prisms rounded at the corners and traversed by several longitudinal ducts are much employed in lengths of about 3 ft. Conduits are made of the same material and molded in the same manner as fireproofing. They are, however, hard-burned and salt-glazed to render them impervious to water.

325. Reinforced Brick Masonry.—Impetus has been given to the use of reinforced brick masonry since 1922 by the results of numerous strength tests * of slabs, beams, and columns, and applications in small structures.

Tests were made in 1932 at the University of Wisconsin on twenty-five 8 by 12-in. beams loaded at the third-points of an 8-ft. span. These beams contained 0.5 to 2.3 per cent of longitudinal steel and variable amounts of Z-shaped steel stirrup reinforcement. The data indicate that formulæ used in designing reinforced concrete beams can be applied to reinforced brick beams provided due attention is given to mortar bond, filling of joints, coursing, and proportion and arrangement of reinforcement. Two beams of Chicago common brick laid in 1L : 3C : 12S mortar (by weight), carrying $1\frac{1}{4}$ per cent of longitudinal steel and a stirrup ratio of 0.0045, gave M/bd^2 values of 397 and 543 lb./in.^{2}. With a stronger brick, a beam having 2.3 per cent of longitudinal steel and a stirrup ratio of 0.0048 failed in compression and developed $M/bd^2 = 840$ lb./in.^{2} and $v = 294$ lb./in.^{2}.

Tests on thirty-two $12\frac{1}{2}$ by $12\frac{1}{2}$-in. brick columns 6 ft. and 12 ft. high, reinforced with longitudinal rods and hoop steel placed in the joints, were also made at the University of Wisconsin. These tests and others made at Lehigh University show that the strength of such a column varies directly with the strength of the plain masonry, and with the percentages of longitudinal and hoop steel. Hoops serve to prevent sudden failures. In the Wisconsin tests a column made with a high-strength brick, 1L : 3C : $7\frac{1}{2}$S mortar, and loaded with $1\frac{1}{2}$ per cent of hoops and 4 per cent of vertical steel carried a maximum load of 5050 lb./in.^{2} on gross area.

Since the integrity of reinforced brick masonry depends upon the development of a strong permanent bond, all joints must be carefully filled. In the lower courses of beams the use of brick of special shapes or tile keyed to the mortar and reinforcement promotes durability of such courses.

Reinforced brick masonry requires little form work and has many architectural possibilities. It appears well suited for buildings, retaining walls, culverts, bridges, reservoirs, sewers, bins, and chimneys.

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* See *Bull.* No. 37, Engr. Expt. Sta., Univ. of Mo.; *Bull.* No. 9 and No. 15, Engr. Expt. Sta., Virginia Poly. Inst.; *Proc. A.S.T.M.*, Vol. 33, Pt. 2, p. 651, and Vol. 34, Pt. 2, p. 387; *Jour. Am. Ceramic Soc.*, November, 1933, p. 584.

CHAPTER IX

PORTLAND CEMENT

326. The Cements of Construction.—The cementing materials which are most used in engineering constructions may be classified as follows:

1. Hydraulic cements	Portland cement Natural cement Puzzolan cement Blended cement High alumina cement	Will set under water
2. Limes	Quick lime Hydrated lime Hydraulic lime (sets under water)	
3. Gypsum Plasters	Plaster of Paris Wall plaster Hard finish plaster	
4. Bitumens		

Only the first three classes will be discussed herein; for the properties and uses of bitumens, reference may be made to *Asphalts and Allied Substances*, by H. Abrahams, and to *Highway Design and Construction*, by A. G. Bruce, or to other standard works on pavements.

Owing to the widespread use and importance of Portland cement as a material of construction, and on account of the necessity for a thorough knowledge of its properties in order to properly fabricate it into structures, we shall consider at some length its nature, manufacture and properties.

NATURE OF PORTLAND CEMENT

327. Definition.—In the specifications for Portland cement the following definition appears.

"Portland cement is the product obtained by finely pulverizing clinker produced by calcining to incipient fusion, an intimate and properly proportioned mixture of argillaceous and calcareous materials, with no additions subsequent to calcination excepting water and calcined or uncalcined gypsum."

328. The Characteristics of Portland Cement.—Although the characteristics of Portland cement are not measures of quality, they often serve to distinguish differences in brand and to separate Portland from other cements. Normal Portland cement is a flour-like powder which varies in color from a greenish gray to a brownish gray. White Portland cement is also successfully produced. In general, the specific gravity of Portland cement is higher than that of other hydraulic cements, lying between 3.10 and 3.20. The specific weight is variable, ranging from 75 to 95 lb. per cu. ft., depending upon the compactness; it is considerably higher than the specific weight of natural cement. Portland cement when mixed with water sets more slowly than natural cement and more rapidly than puzzolan cement.

To meet the demands of various types of construction and differences in exposure, four varieties of Portland cement are now marketed: (1) normal, (2) high early strength, (3) moderate heat, and (4) sulphate-resisting Portland cements.[*] Of these the high-early-strength variety hardens most rapidly and acquires greater strength in a week than any hydraulic cement excepting high alumina cement. The rate of hardening of normal Portland is next in rapidity and that of the sulphate resisting variety is least of the Portlands. They all harden more rapidly than do the natural, puzzolan, or Portland-puzzolan cements.

329. Composition and Constitution of Portland Cement.—*Composition.* The three fundamental constituents of hydraulic cements are lime, silica, and alumina. In addition to these, most cements contain small proportions of iron oxide, magnesia, sulphur trioxide, alkalies, and carbon dioxide. In the manufacture of the high-early-strength cements, additions subsequent to calcination, not exceeding 1 per cent of harmless materials other than gypsum or water, are permitted. The usual limits in oxide composition for normal and for high-early-strength Portland cements produced in the United States are here tabulated from the published analyses of a large number of cements:

	Usual Percentage Limits	
Oxide	Normal Portland	H.E.S. Portland
Lime (CaO)	62–65	63–66
Silica (SiO_2)	19–22	19–21
Alumina (Al_2O_3)	4–7	4–7
Iron Oxide (Fe_2O_3)	2–4	2–4
Magnesia (MgO)	1–4	1–4
Sulphur Trioxide (SO_3)	1.5–2	2–2.5
Alkalies (K_2O+Na_2O)	0.3–1	0.3–1
Water (H_2O) and Carbon Dioxide (CO_2)	1–3	1–3

Although the oxide composition has been the basis of proportioning the raw materials in manufacturing Portland cement, and although good cements are made by following rule-of-thumb methods and giving especial care to details, nevertheless the properties of the mineral compounds formed in the burning process determine the quality of the cement. Studies of the properties of these mineral compounds by petrographers and physical chemists have led to a better understanding of their function in Portland cement and to better methods of proportioning raw materials in manufacture.

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[*] See United States Government Specifications, Govt. Printing Office, Washington.

Constitution.—From the investigations of Le Châtelier,* the French chemist, Törnebohm, the Swedish petrographer, Day, Shephard, Rankin, and Wright † at the Geophysical Laboratory at Washington, and the recent studies of Brownmiller and Bogue ‡ of the Portland Cement Association, it has been shown that the four principal mineral compounds in a well-burned Portland cement are:

1. Tricalcium silicate, $3CaO \cdot SiO_2$ symbolized by C_3S;
2. Dicalcium silicate, $2CaO \cdot SiO_2$ symbolized by C_2S;
3. Tricalcium aluminate, $3CaO \cdot Al_2O_3$ symbolized by C_3A;
4. Tetracalcium aluminum ferrite, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ symbolized by C_4AF.

Under certain circumstances the alumina may be partially combined as $5CaO \cdot 3Al_2O_3 = C_5A_3$, and some uncombined or "free" lime may be present. American cements also usually carry small amounts of free magnesia.

330. The Setting and Hardening of Portland Cement.—If Portland cement clinker is pulverized with 2 or 3 per cent of gypsum and tempered with water, the resulting soft paste slowly loses its plasticity, stiffens, and hardens into a rock-like mass. When the paste has lost its plasticity and become sufficiently coherent to withstand a certain arbitrary pressure, it is said to have acquired *initial set.* On acquiring a rigidity which enables it to withstand a higher intensity of pressure, it is said to have attained *final set.* After final set the paste exhibits a marked increase in rigidity, strength, and hardness with time. This transformation is termed *hardening.*

There has been much dispute concerning the nature of the intricate setting and hardening processes, but there seems to be good evidence to support the following statements concerning the actions of the mineral components in the setting and hardening § of Portland cement mortars and concretes.

1. The flash set of the unadulterated, finely ground clinker is due to the rapid hydration of the aluminates C_3A and C_4AF. The rapidity of the

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* *Constitution of Hydraulic Mortars,* by H. Le Châtelier (trans. by Mack).

† *Engr. News,* Vol. 65, p. 350; also *Jour. Industrial Chemistry,* April, 1911.

‡ *Am. Jour. Science,* Vol. 23 (1932), p. 501; also U. S. Bur. Stds.. *Res. Paper* No. 684.

§ See Portland Cement Assoc. *Fellowship Papers,* No. 17 and 27, by R. H. Bogue and by R. H. Bogue and W. Lerch; also *The Chemistry of Cement and Concrete,* by F. M. Lea and C. H. Desch.

action increases with the proportion of the aluminates present and is regulated by the addition of 2 or 3 per cent of gypsum. The latter reacts with the hydrated aluminates to form fine crystalline needles of calcium sulphoaluminate, which action retards crystallization of the calcium aluminates and thus delays set. The strengthening effects of the aluminates is most potent during the first 24 hours and does not extend beyond 28 days.

2. The action of water on tricalcium silicate, C_3S, proceeds less rapidly, forming supersaturated solutions from which emerge crystals of calcium hydroxide and amorphous masses of colloidal * calcium hydrosilicate. The colloid swells slightly as it takes on water and shrinks as it solidifies into a gel. This gel envelops groups of unattacked cement grains, which are gradually hydrated and further increase the density, impermeability, and strength of the hardened paste. This hydrolysis of the C_3S grains is well under way in 24 hours and has made a marked advance in 7 days. The rate of hydrolysis of C_3S and the character of the gel developed are the main causes for the early hardness and strength of cement pastes.

3. The beta-dicalcium silicate, C_2S, is hydrolized into a gel at a very slow rate. Its influence on strength and hardness is small at ages less than a month, but at one year it contributes proportionately nearly as much strength as does C_3S.

The colloidal theory of setting and hardening of Portland cement was first advanced by W. Michaelis, Sr., in 1893. † Those who believe in this theory maintain that, when a finely ground cement is gaged with water, a supersaturated solution containing calcium oxide, calcium aluminate, calcium sulphate, and calcium ferrite is formed. Owing to the insolubility of the calcium sulphoaluminate in lime water, it crystallizes as previously mentioned. Then the oversaturated solution coagulates in a gel formation about the cement grains, many of which are unattacked. This plastic hydrogel containing calcium hydrosilicate, calcium hydroaluminate, calcium hydroferrite, and a small proportion of lime gradually hardens, partly by withdrawal of water by the unattacked cement grains and partly by crystallization of these components. The hardening of cement in air is hastened by the evaporation of a portion of the water. Owing to

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* There are a number of solids which, when very finely pulverized and mixed with certain liquids in highly supersaturated solutions, will form more or less rigid bodies by coagulation and subsequent desiccation. No crystalline structure is evinced during or after desiccation. On account of the glue-like properties which such substances exhibit in hardening, they have been named colloids. Some substances may form either colloids or crystalloids, depending upon the degree of supersaturation of the liquid solution. Colloidal solutions will not pass through a parchment membrane, whereas crystalloid solutions will. A colloidal aqueous solution is often called an hydrosol. When it becomes gelatinous it is termed an hydrogel. The boiling-point of an hydrosol is the same as the boiling-point of water.

† *Cement and Engineering News* (trans.), Vol. 21, p. 299.

the evaporation of water during air hardening, however, more cement grains are imperfectly hydrated than in water hardening, and shrinkage of the colloid is very marked.

Since crystals are formed from solutions of low supersaturation, Michaelis claimed that the addition of gypsum, which brings on crystallization, will therefore retard the setting process. This follows since, owing to the low supersaturation of the initial mixture, some crystallization must take place before coagulation of the hydrogel.

Michaelis' theory has been partially verified by the microscope. Sections of hardened Portland cement paste have revealed the colloidal structure surrounding grains of unattacked clinker. In fact Stern * estimated that only half of the cement grains are attacked by water in ordinary pastes of cement. That the attack of water is incomplete may be proved by holding the broken ends of cement briquettes in contact under water for several days, after which cohesion will have taken place. It has been demonstrated that the powder formed by crushing and grinding neat cement briquettes has cementitious properties, and briquettes made after a second regrinding have possessed a low strength.

331. The Calculation of Compound Composition of Portland Cements. Bogue † has developed a method for calculating the compound composition from the oxide analysis of a cement. This method is based upon cooling of the clinker at such rate that equilibrium is maintained. Although equilibrium does not usually obtain in commercial operations, valuable information can be derived from such calculations. The method is summarized in the following steps and appended table. An accurate chemical analysis is entered in the first column of the table as shown.

Since the ratio of the atomic weight of $CaO : SO_3 = 56.07 : 80.065 = 0.70 : 1$, each percentage of SO_3 combines with 0.70 per cent of CaO to form 1.70 per cent of $CaSO_4$. Hence the percentage of lime required to satisfy $SO_3 (= 0.7 \times \text{per cent } SO_3)$ is recorded as c_1 in column 4 of the table, opposite CaO, the percentage of SO_3 is also entered in column 4 and the $CaSO_4$ content is summed and entered at the bottom of column 4.

Similarly, since the atomic ratios $Al_2O_3 \; Fe_2O_3 = 101.92 : 159.68 = 0.64 : 1$ and $4CaO : Fe_2O_3 = 224.28 : 159.68 = 1.40 : 1$, it is evident that each percentage of Fe_2O_3 enters into combination with 0.64 per cent of Al_2O_3 and 1.40 per cent of CaO to form 3.04 per cent $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$. Therefore $0.64 \times$ percentage of Fe_2O_3 is entered as a_1, opposite Al_2O_3 in column 5, and $1.4 \times$ percentage of Fe_2O_3 is entered as c_2, opposite CaO in column 5; the percentage of Fe_2O_3 is re-entered in the same column and the percentage of C_4AF is summed at the bottom. 2. [illegible] high, practically none of the magnesia is combined, it is entered as free at the bottom of column 2.

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* *Chemiker Zeitung*, 1908, No. 47 and 85; *Stahl u. Eisen*, Vol. 28, p. 1542; *Kgl. Materialprufungsamt*, Vol. 27, p. 7, and Vol. 28, p. 173.

† Portland Cement Assoc. *Fellowship Paper*, No. 21, *Calculation of Compo ent and Portland Cement.*

The total alumina minus a_1, entered as a_2 in column 6, is available to combine with lime to form C_3A in the ratio $3CaO : Al_2O_3 = 168.21 : 101.92 = 1.65 : 1$. Hence each percentage of this available alumina×1.65 is the percentage of CaO required for C_3A, and it is entered opposite CaO as c_3 in column 6. Summing quantities in column 6 gives percentage of C_3A.

The CaO available to combine with SiO_2 is total CaO minus (free $CaO + c_1 + c_2 + c_3$); call this difference c. Then the total silica (s) is calculated first to combine with CaO to form C_2S. Since the ratio $2CaO \cdot SiO_2 : SiO_2 = 172.20 : 60.06 = 2.87 : 1$, each percentage of $s \times 2.87$ is the percentage of C_2S. This first approximation of C_2S is entered in column 8, opposite SiO_2. By subtracting this value of C_2S from the sum $s + c$, the amount of CaO (call c_4) available for combination with $2CaO \cdot SiO_2$ to form $3CaO \cdot SiO_2$ is determined. Since the ratio $3CaO \cdot SiO_2 : CaO = 228.27 : 56.07 = 4.07 : 1$, multiplying c_4 by 4.07 gives the amount of C_3S which is entered at the foot of column 7. By subtracting this value of C_3S from $c + s$, the true percentage of C_2S is found and entered in column 8.

Should the computed percentage of C_3S be greater than $c + s$, no C_2S is present. In that case the content of C_3S is found from the ratio $3CaO \cdot SiO_2 : SiO_2 = 228.27 : 60.06 = 3.8 : 1$. Hence the percentage of C_3S is obtained by multiplying the percentage of SiO_2 by 3.8. This latter value of C_3S, subtracted from $c + s$, gives the percentage of uncombined lime. This last condition can only obtain when lime is in excess of the amount required for equilibrium and the free lime has not been deducted.

RECORD OF SIGNIFICANT DATA FOR COMPUTING COMPOUND COMPOSITION

Oxides	Analysis	Compounds					
		Free CaO	SO_3+	Fe_2O_3+	Al_2O_3+	c and s	C_2S and C_4
CaO	63.0	0.2	$c_1 = 1.0$	$c_2 = 4.9$	$c_3 = 5.4$	$c = 51.5$	$c_4 = 10.3$
MgO	3.0						
Al_2O_3	5.5	....	....	$a_1 = 2.2$	$a_2 = 3.3$		
Fe_2O_3	3.5	....	....	3.5			
SiO_2	22.0	....	....	....	....	$s = 22.0$	63.2 approx.
SO_3	1.5	....	1.5				
Ig. Loss	1.2						
Ins. Res.	0.1						
Free CaO	0.2						

Ignition Loss	Free MgO	CaO	$CaSO_4$	C_4AF	C_3A	C_3S	C_2S
1.2	3.0	0.2	2.5	10.6	8.7	42	32

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collince errors in cds, dchnical analysis of 0.2 per cent in determinations of solu alumina, silicsolutir iron oxide will make errors up to 1.5 per cent in crysa compounds; will. Whe tinpercentages for the latter should be rounded off to is the numbers. If the ignition loss is high, the analysis should be reduced tinker basis prior to compound calculations.

As previously mentioned, Bogue's method of calculation is based on the assumption that the clinker is slowly cooled at such rate that equilibrium is maintained and the crystallization is complete. Lea and Parker * have shown that values calculated by the Bogue method may be considerably in error if the clinker liquid crystallizes independently of the solids formed, or if cooling is so sudden that no crystallization takes place and glass is formed. For the case of independent crystallization and a clinkering temperature of 1400° C., they show that Bogue's method is correct for cements with Al_2O_3/Fe_2O_3 ratios between 0.9 and 1.7, but for ratios between 1.7 and 6.1 their corrections to be added are:

$$\begin{aligned}&C_3S, \ +(1.8Al_2O_3-2.8Fe_2O_3);\\&C_2S, \ +(2.1Fe_2O_3-1.4Al_2O_3);\\&C_3A, \ +(2.5Fe_2O_3-1.6Al_2O_3);\\&C_4AF, \ \text{Nil.}\end{aligned}$$

Thus for a cement with $Al_2O_3=7$ and $Fe_2O_3=3$ per cent, their correction to $C_3S=4.2$, to $C_2S=-3.5$, and to $C_3A=-3\ 7$ per cent.

For very rapid cooling of the clinker, the liquid is formed into glass and they show that *no* C_3A or C_4AF appear but the amount of glass is $+(2.95Al_2O_3+2.2Fe_2O_3)$. For this case their corrections to Bogue's values for C_3S and C_2S are: C_3S, $+(1.8Al_2O_3-2.8Fe_2O_3)$; C_2S, $+(1.9Fe_2O_3-2.1Al_2O_3)$.

Out of 21 commercial plant clinkers examined at the Bureau of Standards, see *R P 1066*, January, 1938, 11 had 5 per cent or less of glass and 18 had 10 per cent or less.

332. The Proportioning of the Main Constituents.—From what has been said relative to the composition and constitution of Portland cement it will be evident that much care must be exercised by the cement chemist in proportioning the raw materials so that clinker of proper constitution may be obtained after burning. During the past score of years there has been marked tendency to increase the lime content and thereby raise C_3S in order to increase the early strength of mortars and concretes. An excess of lime beyond that combined with silica and alumina, *free lime,* promotes unsoundness in the hardening paste. Unsoundness is characterized by checking and cracking of the hardened paste. Lea and Parker (*loc. cit.*) state that the maximum lime which can be carried is given by $CaO=2.8SiO_2+1.18Al_2O_3+0.65Fe_2O_3$.

According to the German and other European specifications, the weight ratio of $CaO/(SiO_2+Al_2O_3+Fe_2O_3)\lesseqgtr 1.7$, but no limitation is placed on the lime content. The above lime ratio may run to 2.3 or 2.4 for the high early strength Portlands of the United States.

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* See *Building Research Tech. Paper* No. 16 (1935); also *The Chemistry of Cement and Concrete*, by Lea and Desch, p. 119.

Control is exercised over the rate of setting by regulating the ratio $SiO_2/(Al_2O_3+Fe_2O_3)$. Where the development of much heat during hydration is undesirable the silica content is increased to 21 per cent or above, the alumina and iron oxide contents are limited to 6 per cent each, the C_3A is limited to 8 per cent, and the ratio Al_2O_3/Fe_2O_3 is limited between 0.7 and 2.0.* Resistance to the action of sulphate waters is increased by raising the silica to a minimum of 24 per cent, reducing the alumina and iron oxide contents to 4 per cent each, reducing C_3A to 5 per cent, and holding the ratio Al_2O_3/Fe_2O_3 between 0.7 and 2.0.*

In a general way it can be said that raising the C_3S content of a cement is desirable in so far as it renders the clinker easier to grind, promotes strength at early ages, and increases resistance to freezing and thawing; but it has the undesirable effect of increasing the heat of hydration and increasing the solubility of the cement in water. Raising the C_2S content renders clinker harder to grind, reduces early strength, decreases resistance to freezing and thawing at early ages, decreases the heat of hydration, but promotes high strength after a year or more. Raising the C_3A content reduces the time of set, increases strength up to 28 days, but lowers the ultimate strength, increases the heat of hydration, increases the contraction during air hardening, and weakens resistance to sulphate attack. Raising the C_4AF content appears to reduce strength slightly.

333. Iron Oxide.—Ferric oxide (Fe_2O_3) exercises a very important influence on the color of the cement. Pure white cements are made from materials containing very little of this compound. Most cements contain 2 to 3 per cent of this oxide. If it enters into combination with lime and alumina to form C_4AF, it serves to neutralize some of the undesirable properties contributed by alumina when combined with lime alone. When iron oxide is combined with lime as $2CaO \cdot Fe_2O_3$ it promotes instability. Small percentages of iron oxide render highly silicious raw materials easier to burn, but a high iron content produces a hard clinker which is difficult to grind.

334. Magnesia in ordinary proportions does not combine with the other elements in burning. It hydrates very slowly when tempered with water but expands markedly after a long attack.

The percentage of magnesia which can be safely carried in Portland cement has been the subject of much experimentation with variable results. Tests by P. H. Bates at the Bureau of Standards on cements made from clinker burned in a small gas-fired rotary kiln showed normal results in setting, in soundness, and in strength up to one year, when the magnesia content was less than 7.5 per cent (*Cement Age*, Cement Mill Ed., March, 1914). In 1934, H. F. Gonnerman of the Portland Cement Association Laboratory reported an extended series of tests to the A.S.T.M., showing the effects of magnesia on strength, durability, and volume change. His tests indicated undesirable properties in cements containing over 5 per cent magnesia. Tests by Prof. E. D. Campbell at the University of Michigan on neat prisms made of cements containing 3 per cent of free magnesia exhibited over 1 per cent expansion after 13 years immersion in cold water, although the one-year expansion was normal.

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* See Federal Specifications.

Since magnesia can be locked up in the glass formed by sudden cooling of the clinker, it seems likely that some of the discrepancies in the tests described are due to differences in the proportions of *free* magnesia. Because of the detrimental effects of free magnesia on strength and expansion after prolonged hydration, the magnesia content of Portland cement is limited. In American specifications the maximum allowed is 5 per cent.

335. Sulphur Compounds.—Sulphides in cements tend to cause unsoundness. Ordinarily they are not present in harmful amounts in Portland cement clinker. The sulphate of calcium, gypsum ($CaSO_4+2H_2O$), is added after burning in amounts less than 3 or 4 per cent to retard setting. The hydration of gypsum also appears to counteract to some extent the weakening attending the hydration of the aluminates In specifications for normal Portland cements the limit on SO_3 is 2.0 per cent. For the high-early-strength Portlands the limit is raised to 2.5 per cent.

336. The Alkalies (K_2O and Na_2O) are found in very small amounts in most Portland cements. There are some indications that they enter into combinations with lime and alumina. The major influence of these oxides appears to be the acceleration which they produce in setting.

337. Water and Carbonic Oxide.—Aeration of cement clinker, which is commonly practiced to slake free lime, also causes an absorption of some moisture and carbon dioxide. The per cent CO_2 absorbed is dependent on the completeness of the exposure to air, as an experiment by Butler (see Butler's *Portland Cement*, p. 317) demonstrates.

He placed a part of a sample of sound cement containing 0.25 per cent CO_2 in a cask, and part he spread out in a thin layer on a tray. At twenty-eight days the sample in the cask contained 0.57 per cent CO_2 and the sample in the tray 1.82 per cent; the corresponding percentages after three years were 3.21 and 5.60. The tensile strength of the original sample showed a progressive increase during this time interval. From these results he concluded that the percentage of carbon dioxide in a cement is not an indication of free lime.

The amount of moisture absorbed by cement is dependent principally on the completeness of exposure and the moisture in the surrounding atmosphere. Absorption of moisture tends to increase the time of setting, but absorption of CO_2 accelerates setting.

American specifications limit the loss on ignition, which is due mainly to the presence of water and carbonic oxide, to 4 per cent.

MODERN METHODS OF MANUFACTURE

338. Growth and Importance of the Portland Cement Industry.—On account of the many excellent properties possessed by Portland cement, its great field of usefulness, the widely distributed sources of the raw materials from which it is made, its cheapness, and the decline in the supply of timber, the Portland cement industry has had a marvelously rapid growth. Although the process of manufacture of this material was patented in 1824, by Joseph Aspdin, of Leeds, England, it was not until 1859 that any considerable quantity was used in England, and not until 1875 that any progress was made in the manufacture of this cement in the United States. An estimate of the rapidity of growth and the economic importance of this industry may be formed by comparing the quantity produced in 1880—42,000 bbl.—with the output for the United States in 1937—116,174,708 bbl. The value per barrel at mill in 1880 was $3, in 1937 it was $1.48.

The following percentages show the trend in modern usage of Portland cement: for roads and pavements, 23; buildings and similar structures, 34; conservation projects, 14; rural uses including products for farms, 9; sewerage and drainage, 7; bridges, 4; miscellaneous, 9.

339. Raw Materials.—In general the calcareous ingredients are present in raw materials in the form of lime carbonate ($CaCO_3$) and the silica and alumina are combined in the form of clay or other argillaceous ingredients. These essential ingredients are proportioned in accordance with the principles mentioned in Art. 332.

Arranged in order of importance, the raw materials most commonly used in the manufacture of Portland cement and the parts of the United States in which they are employed are:

MATERIALS		WHERE USED IN MAKING PORTLAND CEMENT
CALCAREOUS	ARGILLACEOUS	
1. Limestone	+ Shale or Clay	Widely used, N. Y., Mich., Ill., Ind., Cal., Ia., Kan., and Tex.
2. Limestone	+ Cement rock	Eastern Penn., N. J., Cal., and Kan.
3. Limestone	+ Blast furnace slag	Illinois, Ohio, Penn.
4. Marl	+ Shale or Clay	Central N. Y., Ohio, Mich., Ind.

Limestone for the manufacture of Portland cement should be soft and consist largely of calcite or calcite and clay. If 20 per cent or more of clay is present with the calcite it is called cement rock. The limestone should not contain over 5 or 6 per cent of magnesium carbonate and should be comparatively free from sulphur and quartz. According to Eckel * phosphorus pentoxide (P_2O_5) is also an undesirable element.

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* Eckel's *Cements, Limes and Plasters,* p. 389.

Marl, another calcareous substance much used in the wet process of manufacture, is a soft deposit found in the bottoms of shallow lakes, swamps and extinct fresh-water basins. It should conform to the restrictions placed upon limestone and be free from sand and gravel.

For origin and composition of clays, reference should be made to Art. 275, Ch. VIII.

With reference to the proportions of the constituents of clay suitable for Portland cement manufacture, Meade states that the ratio of the silica to the alumina content should be between 2.5 and 4 to 1, that there should not be more iron oxide than alumina, and that the alkalies and magnesia should each be less than 3 per cent.* A considerable proportion of sand larger than a 100-mesh sieve renders the clay unfit for cement manufacture.

Blast furnace slag suitable for the manufacture of Portland cement should be basic in character. The analysis should conform roughly to the following: Two-fifths to one-half lime, one-third silica, one-eighth to one-sixth alumina plus iron oxide, magnesia less than 3 per cent. Calcium sulphide is considered undesirable.

The first step in the process of manufacture of Portland cement is the winning of the raw materials from nature. Hard raw materials are blasted, loaded on to small cars, and drawn to the cement mill. Soft materials like marl or clay are dug or excavated by steam shovel or dredge, depending upon the nature of the deposit. Such materials are often pumped directly to the mill. Slag is granulated into a sand-like substance by running the molten material from the blast furnace into a vat of water. It is then loaded on cars by clam-shell buckets and transported to the cement plant.

THE DRY PROCESS OF MANUFACTURE

340. Preparation of Raw Materials.—In general, only the comparatively dry raw materials, such as limestone and cement rock, limestone and shale or clay, and limestone and blast furnace slag, are used in the dry process of manufacture of Portland cement. The steps in the process of manufacture are: 1, crushing of raw materials; 2, drying; 3, grinding; 4, proportioning; 5, pulverizing of raw materials; 6, burning; 7, cooling and storing the clinker; 8, adulteration to retard set; 9, reduction of clinker to an impalpable powder; 10, seasoning of cement; 11, bagging. The order of the first four of these operations varies at different plants and it is dependent to some extent upon the character of the raw materials.

The hard materials are usually crushed in gyratory crushers, although jaw and roll crushers of large capacities are also used. Generally, the material must be passed through a large and a small crusher in order th the requisite fineness for successful operation of the grinding mills may result.

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* Meade's *Portland Cement*, p. 54.

Since it is necessary to have the raw materials in an approximately dry state before grinding, most of these materials must be passed through some sort of a drying apparatus. In most plants a dryer consists of a hollow steel cylinder about 50 ft. long and 5 ft. in diameter, revolving about its geometrical axis which is inclined at a small angle with the horizontal. The raw materials enter at the upper end and pass out at the lower end of the cylinder. The source of heat, which is commonly an attached furnace or waste gas from the rotary kilns, enters at the lower end and passes out at the upper. To increase the circulation of the materials through the hot gases, lugs which serve to elevate and scatter the charge, are riveted on the inside of the dryer.

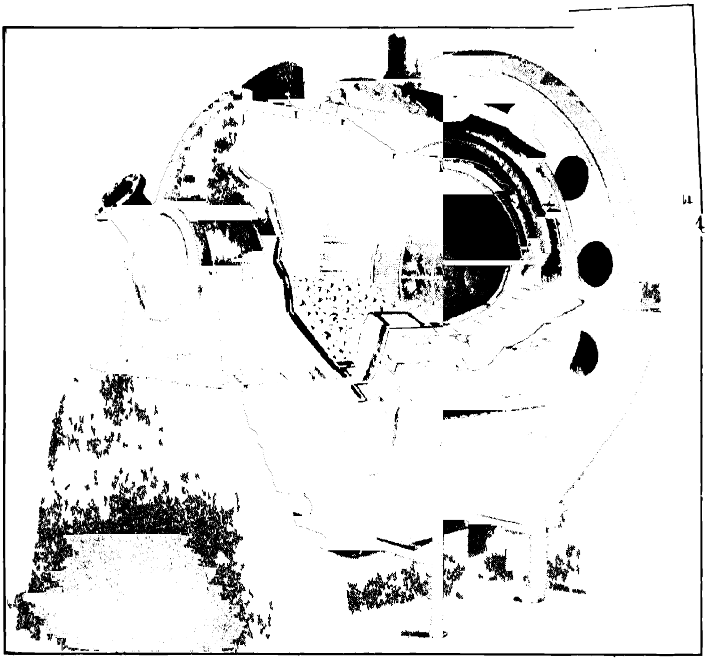

Fig. 1.—An Allis Chalmers Dry Grinding Preliminator.

341. Preliminary Grinding.—In order to secure proper combination in the kiln between the lime, silica, and alumina, it is necessary to have the raw materials ground so finely that 90 per cent will pass a No. 200 mesh. This is usually done in two stages, preliminary and final.

Preliminary grinding is quite extensively done in some type of ball mill. One of the latest forms of such machine is the preliminator shown in Fig. 1. The preliminator consists of a cylindrical steel drum lined with chilled iron or hard steel and equipped with trunnions. The right end of the drum is encircled by a large gear by means of which the mill is rotated. Through a hole in the left trunnion raw material is fed into the mill. Pulverizing is accomplished by the rolling and hammering received from six to eight tons of forged steel balls which range in diameter from 2½ in. to 5 in. The ground material passes through narrow longitudinal slots shown near the right end of the mill onto a circumferential screen. Residues are returned to the grinding compartment. The fines pass through the screen and are chuted to a conveyor. Working on 3-in. limestone and shale, a preliminator 8 ft. in diameter and 5½ ft. long can produce about 50 bbl. per hour of material which will pass a No. 20 mesh.

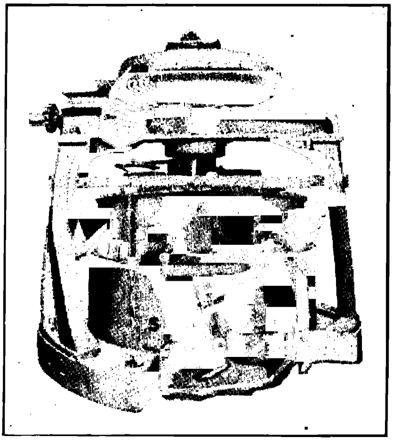

Fig. 2.—A Hercules Mill.
(Courtesy Bradley Pulverizer Co.)

The Hercules mill shown in Fig. 2 has come into extensive use for preliminary grinding of either raw materials or clinker. The material enters the grinding chamber through 3 chutes (*c*). Pulverizing is accomplished by 3 rolls (*r*) which revolve at approximately 375 r.p.m. about a vertical central axis and crush the material against a circumferential die (*d*). The fines pass through the circumferential screen (*s*) surrounding the grinding chamber and are collected in a downspout below the mill. The makers claim that this mill, equipped with a 350-hp. motor will reduce in one hour 40 to 60 tons of dry raw mix, or 135 to 200 bbl. of clinker up to 2½ in. diameter, to the following fineness: 90 to 95 per cent through a 20-mesh, 45 to 55 per cent through a 100-mesh, and 35 to 45 per cent through a 200-mesh sieve. A Hercules mill and a tube mill provide a flexible combination of grinding units with low power consumption.

342. Proportioning.—Since correct proportioning of the raw materials is of prime importance in securing a clinker of proper constitution, accurate automatic scales are installed for weighing the raw materials. This operation can usually be done best after the preliminary grinding of the raw materials; although at some plants, where the raw mix runs very uniform in character, the proportioning is done earlier in the process.

343. Final Grinding.—At many plants the final stage in grinding is done in a tube mill. This mill is also a steel-jacketed cylinder revolving about its geometrical axis. Commonly, such a mill is about 26 ft. long and 7 ft. in diameter. The inside is lined with alloy steel or chilled cast iron. The mix from the preliminary mills or proportioning scales is fed by a worm through one trunnion into the tube mill. Pulverizing is accomplished by the impact and abrasive action of a heavy charge of cast-iron slugs between 1 and 1¼ in. in diameter. A 7 by 26-ft. tube mill will reduce about 30 tons of raw material per hour 80 per cent to pass a 200-sieve, or reduce 70 bbl. of clinker to cement, 90 per cent passing a 200-sieve.

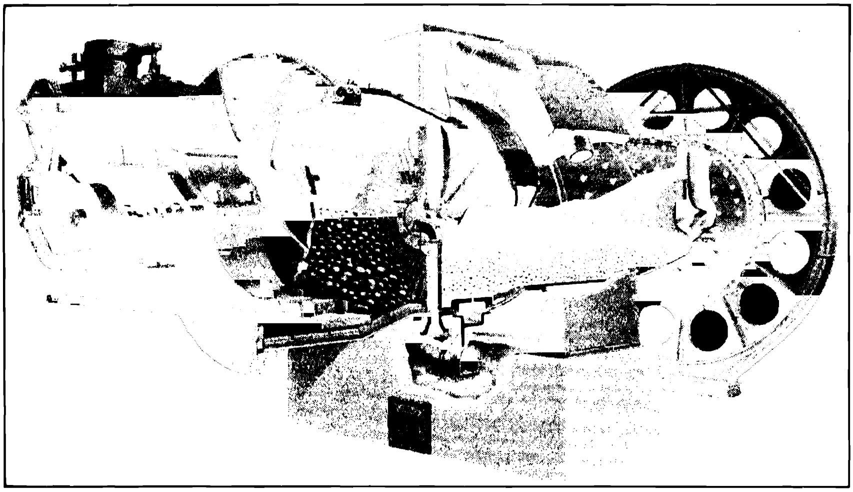

Fig. 3.—A Wet Grinding Compeb Mill (Allis-Chalmers).

The Allis-Chalmers Mfg. Co. claims that a much greater efficiency can be obtained in grinding operations by dividing the drum of the tube mill into compartments by means of one or more transverse diaphragms. Fig. 3 shows one of their Compeb mills suitable for wet grinding, but which can be modified for dry grinding. By the use of such mills the company claims the preliminary grinding can be done in the short compartment and the final grinding in the long compartment. The efficiency is said to be increased by inserting a vibrating screen between the preliminator and the second compartment and by using an air separator to remove the fines in the latter. Added efficiency is claimed for two stages in the final grinding with air separators applied on each compartment to remove the fines as they accumulate. With their No. 726 mill equipped with a 500-hp. motor, the company claims raw material may be dry-ground from 1-in. mesh to 80 per cent through a 200-mesh at 22 tons per hour, or ground wet at 25 tons per hour. On clinker, with air separation, 64 bbl. per hr. with 90 per cent through a 200-mesh sieve is claimed for that mill.

344. Burning.—The purpose of burning the raw mixture is to secure a union of the different constituents in the form of mineral compounds, primarily the formation of silicates of lime and alumina as we have seen in Art. 329.

After the raw materials have been proportioned, intimately mixed, and very finely ground, the powdered product is conveyed to kilns to be burned. Formerly the vertical intermittent type of kiln, somewhat like that used in the production of natural cement, was employed to burn Portland cement. In Europe, use is still made of this type, and in Germany the Hoffman ring kiln is quite extensively employed. However, in the United States the continuously operated rotary kiln is favored to the exclusion of all others.

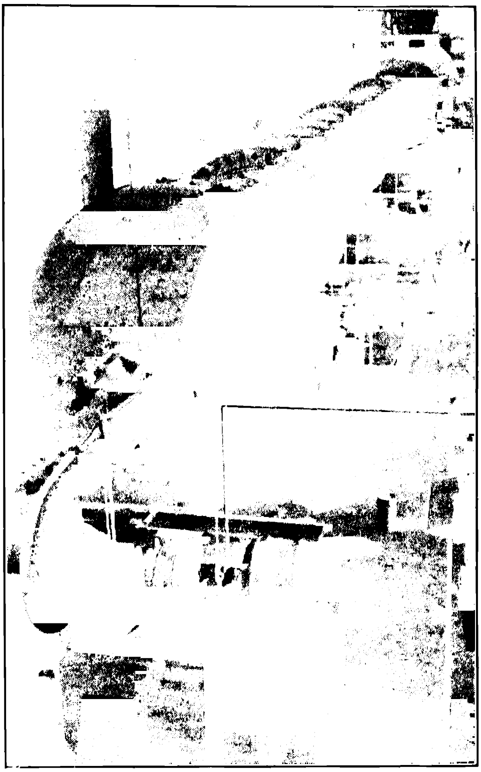

FIG. 4.—An 8½ by 10 by 260-ft. Rotary Kiln for Dry Process. (Allis-Chalmers.)

From Fig. 4 one can obtain a notion of the appearance of a rotary kiln. It consists of a cylindrical jacket made of riveted steel plates lined with refractory fire bricks. The lower end of this cylinder is covered by a detachable hood provided with two openings. Through one of these openings is passed a nozzle for the admission of fuel. The fuel most commonly employed is powdered coal. In order to introduce the coal into the kiln and to secure both rapid and complete combustion, it must be so finely pulverized that 95 per cent will pass a No. 100 sieve. The coal is blown through the nozzle by an air blast. The second opening in the hood is provided to enable the operator to observe the interior of the kiln during calcination. The steel jacket is surrounded by two or more heavy steel tires, by means of which it is rotated on friction roller bearings. These bearings are so adjusted that the axis of the kiln has an inclination with the horizontal of about ½ in. per foot. By thus inclining the axis, the material is slowly moved downward from the upper end as the kiln is rotated. Rotation is produced by a motor placed near the center and geared to a girth gear attached to the jacket. The upper end of the kiln enters a brick flue from which the products of combustion escape to the stack. Passing through this flue is an inclined spout which discharges the finely powdered raw material into the kiln.

Soon after the entrance of the material, it begins to ball up into small marble-like shapes. During the first half of the passage toward the hood any entrained water is evaporated and the material is heated to a temperature sufficient to expel carbon dioxide (CO_2) from the limestone. By the time the clinker has reached within a few feet of the lower end of the kiln its temperature has risen to 1400 or 1450° C., all carbon dioxide sulphur, and organic matter have been expelled, and the little soft yellowish-brown balls have now partially fused into hard, greenish-black clinker.* At many plants the degree of calcination is left to the skill of the burner, who regulates the speed of rotation of the kiln so that the clinkering zone is kept back a few feet from the discharge end. He is able to judge of the position of this zone by the abrupt change in the color of the flame where the material begins to burn and form clinker. Under ordinary conditions a speed of 45 or 60 revolutions per hour secures the requisite degree of calcination. At the end of about one hour the burning process is completed and the clinker falls out of the kiln through a trap in the lower side of the hood, whence it is conveyed to the cooler. The clinker is quite irregular in shape and varies from the size of a hen's egg down to a buckshot. It is very hard, has more or less vitreous luster, and is generally black or greenish-black in color.

In the dry process, kilns usually vary from 150 to 250 ft. in length and 8 to 10 ft. in diameter. The larger modern kilns will produce 1000 to 1400 bbl. of clinker per day. In producing a 376-lb. barrel of Portland cement, by this process, 500 to 600 lb. of raw materials and 70 to 90 lb. of coal, or the equivalent, are consumed.

345. Grinding of the Clinker.—To facilitate grinding, the clinker is passed through a cooler. Frequently the cooler consists of a vertical or horizontal steel cylinder equipped with devices for agitating the material in a forced air draft, which rapidly lowers its temperature. Rapid quenching of the clinker promotes the formation of glass, which action appears to counteract the detrimental influences of tricalcium aluminate and magnesia. After seasoning, about 2 per cent of gypsum is added to retard the time of set of the resulting cement. The adulteration is often done after

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* For further information concerning the chemical changes in a rotary kiln, see R. K. Meade's *Portland Cement*, pp. 176 to 199.

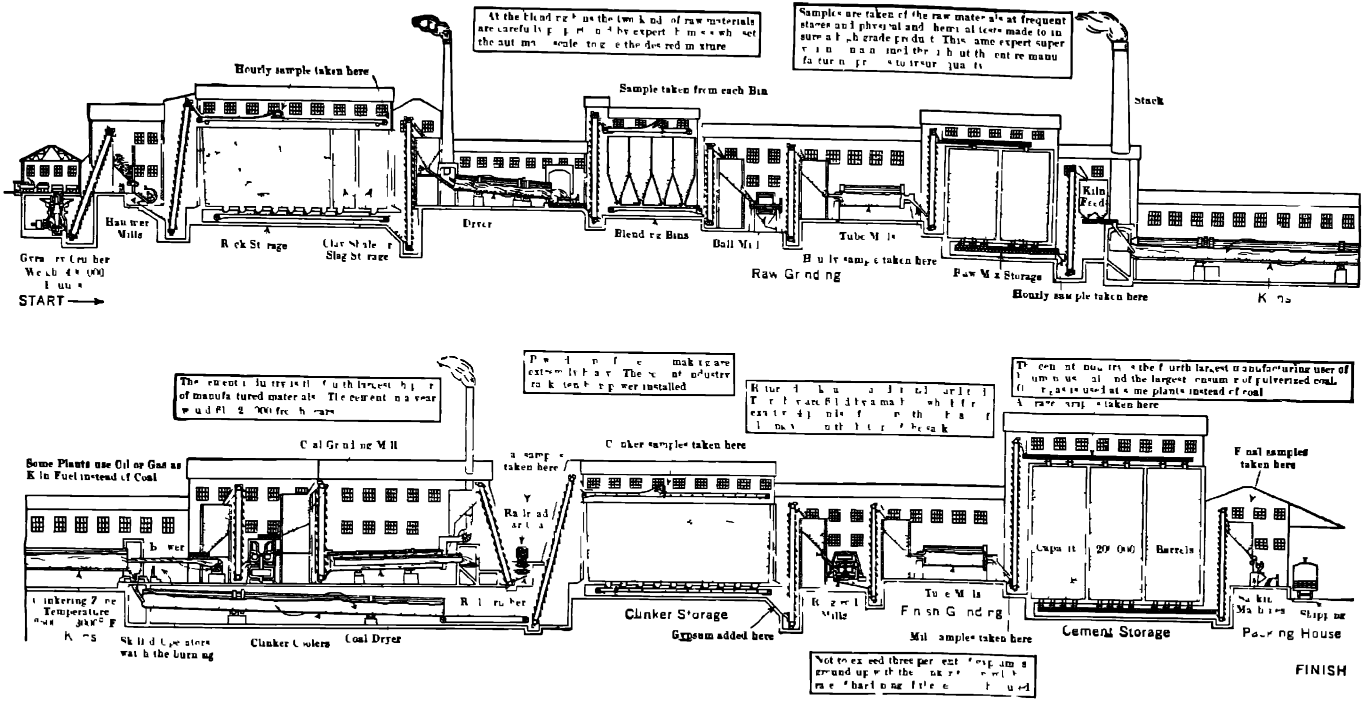

FIG 5.—Sequence of Operations in the Manufacture of Portland Cement by the Dry Process.

(Courtesy of Portland Cement Association.)

the clinker has been through the ball mill. In grinding the clinker the same kind of machinery is generally used as is employed in pulverizing the raw materials. Whatever grinding machinery is used, the resultant fineness is such that 90 to 95 per cent will pass a sieve with 200 meshes per linear inch. For the high-early-strength Portlands the percentage passing this sieve is usually over 96.

346. Storage and Bagging of Cement.—From the grinding mills a conveyor carries the cement to the storage bins, in which it is generally kept for a few weeks before being bagged for shipment. This seasoning period reduces the heat which the cement will generate during setting and hardening. Storage also allows time for free lime to hydrate and carbonate and thus become inert.

In accordance with the demand of the trade the cement is conveyed from the storage bins to the packing house. Here it is automatically weighed and packed by machines sometimes in wooden barrels containing 376 lb., net, but usually in cloth or paper sacks which hold 94 lb. net. Cement is often shipped in bulk to central proportioning plants.

347. Typical Dry-process Plant Operation.—The schematic drawing, Fig. 5, shows the sequence of operations and more important steps in the manufacture of Portland cement by the dry process.

THE WET PROCESS OF MANUFACTURE

348. General.—Although the dry process has been much used in the United States, the advent of longer kilns and waste heat boilers has effected such economies in wet process operations that most of the new installations are of this type, and more cement is now produced by the wet than by the dry process in this country. Where marl is used it is excavated by an orange-peel bucket or pumped in thin mud form from the deposit to tanks near the kilns. The clay is excavated by a steam shovel and ground in a wet pan or in a dry pan, Fig. 1, Ch. VIII. Limestone, when used, is quarried in the usual manner and ground in a ball mill or preliminator. Next the marl and clay, or the limestone and clay, are mixed in predetermined proportions and then ground. This mixture, called slurry, containing from 30 to 50 per cent of water, is placed in storage tanks and held there until analyzed and corrected to the desired composition. The slurry is then pumped into especially constructed long rotary kilns, which in the newer installations are 200 to 400 ft. in length, and burned. The succeeding steps in manufacture are similar to those used in the dry process.

Figure 6 shows an Allis-Chalmers flow-sheet for a typical wet-process plant equipped with classified wet grinding on the raw side. The company's recommendations for installations of vibrating screens, air-quenching clinker cooler, and air separators are also indicated. A slurry thickener and filters are also shown immediately before the kiln.

349. Comparison of Wet and Dry Processes.—The chief advantages of the wet process are the low cost of excavating and grinding raw materials, the accurate control of composition and homogenity of the slurry, and the economical utilization of fuel through the elimination of separated

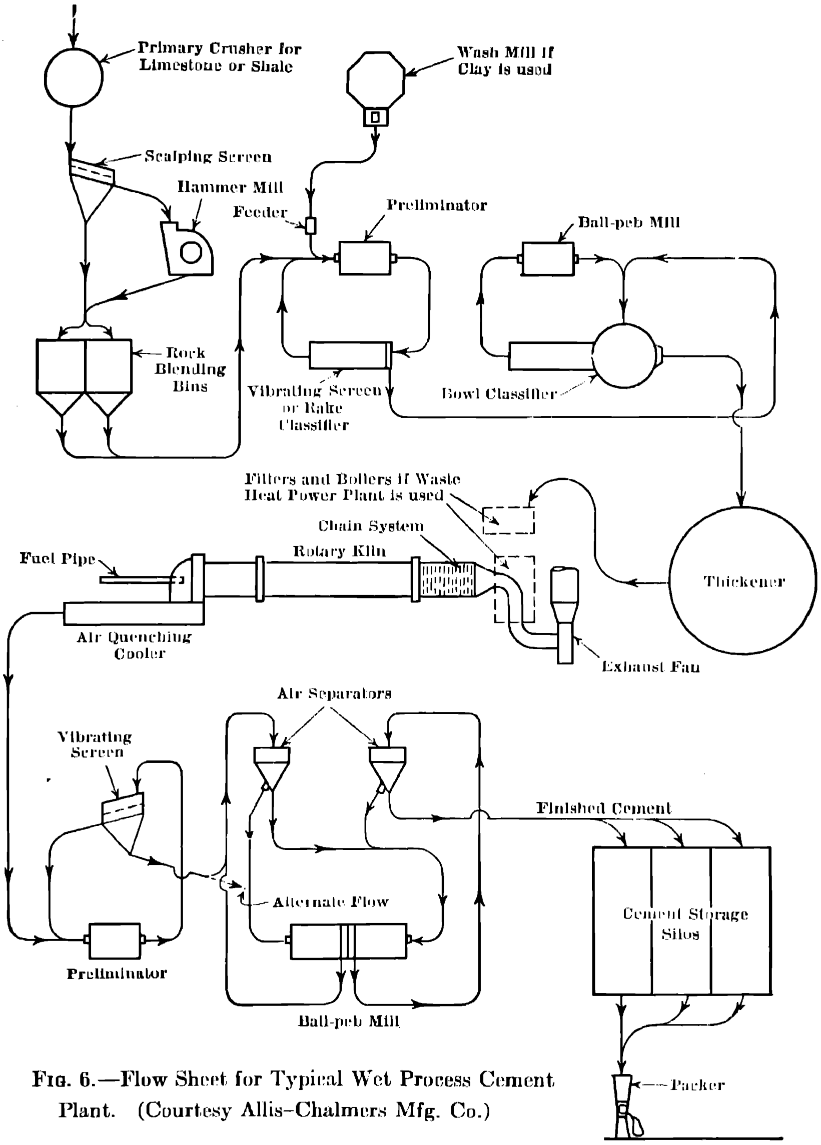

FIG. 6.—Flow Sheet for Typical Wet Process Cement Plant. (Courtesy Allis-Chalmers Mfg. Co.)

drying operations. On the other hand the longer kilns, essential in the wet process, cost more and are less responsive to a variable clinker demand than the short kilns which can be used in the dry process.

In Germany the Lepol kiln has recently been developed to utilize the heat from the kiln so effectively that only 43 to 45 lb. of coal are required to burn a barrel of clinker. This is accomplished by nodulizing the finely ground raw mix by the addition of small amounts of water, and subjecting the nodules to decarbonization prior to admission to the kiln. Perhaps the advent of this kiln will increase the use of the dry process in America.

EFFECTS ON PROPERTIES DUE TO CONDITIONS OF MANUFACTURE OR TESTING

350. Conditions Affecting Soundness.—Although some of the effects of the chemical elements present in Portland cement have already been referred to, it will not be amiss to recall them in considering the properties affected.

The cause most commonly ascribed for unsoundness in Portland cement is the hydration of uncombined lime incased within the cement particles. High burned, coarsely ground, free lime hydrates slowly, but ultimately with sufficient violence to endanger the integrity of the surrounding mortar. Exposed, finely ground, free lime, in small percentages at least, will hydrate before the cement sets and produces no injurious effect. The presence of uncombined lime may be the result of either underburning the clinker or overliming the mixture before burning. Infrequently freshly ground cement will be unsound due to the presence of uncombined lime which may be partially exposed in the grinding process. By allowing the cement to aerate for two or three weeks, thus allowing the lime to hydrate, it is often possible to overcome unsoundness.*

Other chemical elements which may produce unsoundness are magnesia and the alkalies. In most cements the proportions of these elements are well within the danger limit.

It is probable that the action of the retardant assists in overcoming unsoundness, since it tends to hold the mixture in a plastic state and permit the lime to slake. Meade cites several examples of unsound cements which were rendered sound by adding from 0.5 to 3.0 per cent of plaster of Paris.†

Fine grinding of both raw materials and the clinker are very essential if a sound cement is to be secured. Fine grinding of the raw materials makes possible the production of a more homogeneous mixture before burning so that a uniform distribution of the lime content may obtain. It has also been shown that coarsely ground cements which are unsound in the accelerated test may often be rendered sound by fine grinding.* Remembering that the addition of free lime in small percentages does not affect the soundness of a normal Portland cement, it seems evident that the coarser grains of cement may imprison minute particles of uncombined lime which do not become hydrated until after the cement has set. The expansion, which then occurs due to the crystallization of calcium hydrate, produces disintegration. This view seems to be quite generally held by authorities on this subject. The reasonableness of the above explanation of the action of the coarser particles in promoting unsoundness is made more evident by the experiments of Brinckley.† The results of his tests show that the particles of a cement passing a No. 100 and caught on a No. 200 sieve may have some hydraulic properties but that pats made of them break down when subjected to the soundness test. (Art. 419.)

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* For example see *Proc. A.S.T.M.*, Vol. 3, p. 376.

† *Portland Cement*, p. 474. See *Free Lime in Portland Cement* by Kiefer, *Chem. Engr.*, Vol. 15, p. 219; also *Soundness Tests of Portland Cement*, by Taylor, *Proc. A.S.T.M.*, Vol. 3, p. 374.

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 46.....	56	24	0	16	1	3.2	0.1
No. 6.....	41	39	0	14	3	3.0	0
No. 45.....	28	52	0	15	2	3.1	0

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 42.....	61	17	7	12	0	3.1	0.2
No. 24.....	41	37	7	12	0	2.8	0
No. 41.....	29	49	7	12	0	3.0	0

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 58*....	62	13	14	7	0	3.3	0.7
No. 2B Dupl.	43	32	15	7	0	2.9	0.2
No. 37.....	16	58	16	6	0	3.0	0.2

*Cement Double Burned

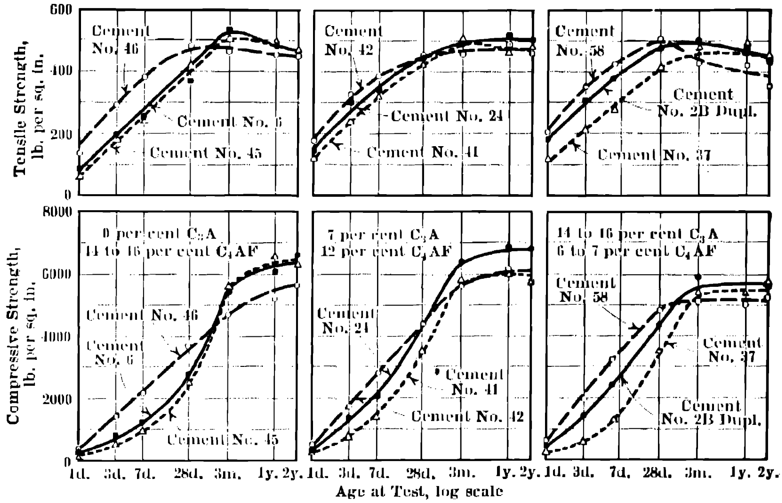

FIG. 7.—Age-Strength Relations for Cements Differing in Tricalcium Silicate Content. (H. F. Gonnerman, *Proc.* A.S.T.M., Vol. 34, Pt. 2, p. 244.)

351. Conditions Affecting Strength.—Recapitulating, we will recall that either a high lime or high alumina content tends to make the cement strong at an early age. Gypsum and plaster of Paris in small percentages also tend to increase the strength of Portland cement, but when present in quantities larger than 3 per cent these substances produce variable effects.*

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* *Portland Cement*, p. 472.

† *Engr. Record*, Vol. 61, p. 212.

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 45.....	28	52	0	15	2	3.1	0
No. 6.....	41	39	0	14	3	3.0	0
No. 11.....	51	29	0	15	2	3.0	0.1
No. 46.....	56	24	0	16	1	3.2	0.1
No. 61.....	55	24	0	16	1	3.1	0.1
No. 62*....	74	5	0	15	2	3.1	0.4

*Cement Double Burned

$C_3A = 0$ per cent
$C_4AF = 14$ to 16 per cent

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 41.....	29	49	7	12	0	3.0	0
No. 24.....	41	37	7	12	0	2.8	0
No. 4.....	43	34	7	13	0	3.1	0
No. 59.....	52	26	6	13	0	2.9	0.6
No. 9*....	53	25	7	13	0	3.0	0
No. 60.....	55	20	7	12	0	3.0	2.3
No. 60A....	57	20	6	13	0	2.8	0.2
No. 42.....	61	17	7	12	0	3.1	0.2

$C_3A = 6$ to 7 per cent
$C_4AF = 12$ to 13 per cent

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 37.....	16	58	16	6	0	3.0	0.2
No. 8 Dupl.	42	33	15	7	0	3.1	0.1
No. 2B Dupl.	43	32	15	7	0	2.9	0.2
No. 57.....	45	28	15	7	0	2.9	2.1
No. 2B.....	47	26	16	7	0	3.0	0.3
No. 38A*...	61	14	14	7	0	3.3	0.3
No. 58.....	62	13	14	7	0	3.3	0.7

$C_3A = 14$ to 16 per cent
$C_4AF = 6$ to 7 per cent

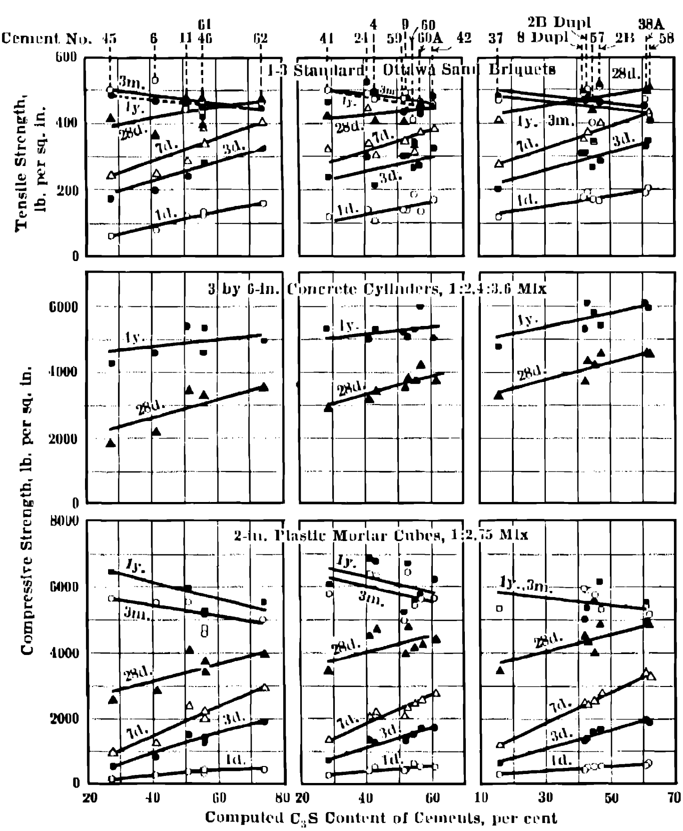

FIG. 8.—Relations of Strength to Tricalcium Silicate Content of Cement. (H. F. Gonnerman, loc. cit.)

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* See results of experiments given in Eckel's *Cements, Limes, and Plasters*, pp. 536–544 (out of print); also a paper by P. H. Bates in *Proc. A.S.T.M.*, Vol. 15, p. 126.

However, it is certain, as has been mentioned before, that the compounds formed determine the properties. As evidence of the effects of variations

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 50*....	47	37	4	8	0	3.0	0.5
No. 16.....	42	38	9	6	0	2.9	0.9
No. 53*....	47	35	10	4	0	3.0	0.3
No. 28.....	44	34	11	6	0	2.8	0.3
No. 2B Dupl.	43	32	15	7	0	2.9	0.2
No. 57.....	45	28	15	7	0	2.9	2.1
No. 8 Dupl.	42	33	15	7	0	3.1	0.1
No. 2B.....	47	26	16	7	0	3.0	0.3
No. 1.....	43	27	18	4	0	2.8	1.4
No. 1 Dupl.	45	28	20	4	0	2.9	0.2

$C_4AF = 4$ to 8 per cent

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 6.....	41	39	0	14	3	3.0	0
No. 51.....	38	45	2	13	0	3.3	0
No. 26.....	42	38	3	15	0	2.7	0
No. 4.....	43	34	7	13	0	3.1	0
No. 24.....	41	37	7	12	0	2.8	0
No. 29.....	40	33	11	13	0	2.8	0
No. 12.....	41	32	12	12	0	2.8	0.1
No. 20.....	42	30	12	13	0	2.8	0
No. 30.....	39	32	13	13	0	2.8	0.1

$C_4AF = 12$ to 15 per cent

Cement	C_3S	C_2S	C_3A	C_4AF	C_2F	MgO	Free CaO
No. 19.....	44	33	0	19	1	2.5	0
No. 27.....	41	35	1	20	0	2.0	0
No. 17.....	39	37	3	18	0	2.9	0
No. 25.....	44	32	4	18	0	2.5	0
No. 23.....	38	33	5	20	0	2.8	0
No. 13.....	38	31	7	21	0	2.7	0
No. 21.....	40	30	10	17	0	2.8	0

*Cement Double Burned

$C_4AF = 17$ to 21 per cent

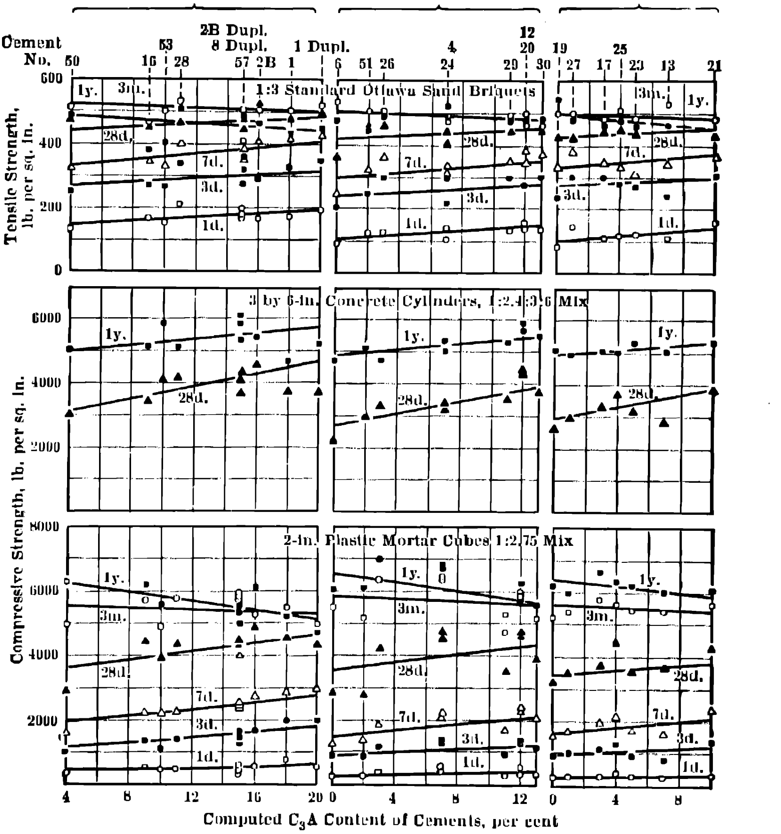

FIG. 9.—Relations of Strength to Tricalcium Aluminate Content of Cement. (H. F. Gonnerman, loc. cit.)

in tricalcium silicate, C_3S, and tricalcium aluminate, C_3A, on the strengths of cement mortars and concretes, Figs. 7, 8, and 9 have been inserted from the 1934 tests of Gonnerman at the Portland Cement Association Laboratories. The cements were prepared from commercial raw materials and carefully burned in an experimental kiln. The effects of C_3S and C_3A in producing high early strengths are patent in all three diagrams. It is also apparent that the strengths at a year or more of the mortars of cements having high C_2S contents are as high or higher than those containing cements of high C_3S contents. At ages of a year, Fig. 9 indicates that high C_3A contents are detrimental to the strengths of mortars and to some of the concretes.

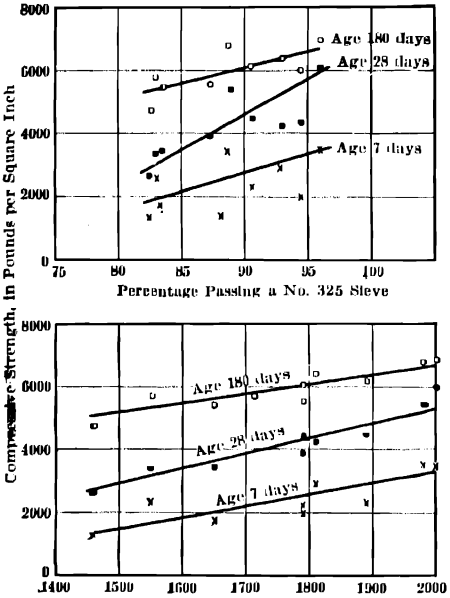

FIG. 10.—The Effect of Fineness of Cement on the Compressive Strength of Mortar.

In addition to effects of composition, the strength of cement is greatly influenced by the degree of burning, the fineness of grinding, and the aeration it receives. If underburned the cement is likely to be deficient in strength. Assuming the clinker properly burned, increasing the proportion of fine particles between 5 and 20 microns (1 micron = 0.001 mm.) in diameter causes an increase in mortar or concrete strength. It appears questionable if there is material advantage to be gained from particles below 5 microns in diameter, and those above 100 microns exhibit no cementitious properties.

In Bates' experiments (*Proc. A.S.T.M.*, Vol. 15, p. 126) the effect of fineness of grinding on the compressive strength of 1 : $1\frac{1}{2}$: $4\frac{1}{2}$ concrete was determined. Ten brands of cement, varying in fineness from 75.4 to 82.2 per cent passing a 200-mesh sieve, were used as received and also after being reground so that the fineness of the individual brands varied from 86.8 to 92.7 per cent passing the same sieve. At an age of twenty-eight days the concrete made from the finer cements exhibited an average strength of 28 per cent greater than the concrete made from the normal cement. At ninety days the concrete made from the finer cements averaged 17 per cent more strength.

The relation of the compressive strength of 1 : 3 standard sand mortars to the surface area of the particles of commercial cements of like composition is well shown in Fig. 10.* Since all nine of the cements represented in Fig. 10 had residues less than 10 per cent on the No. 200-mesh sieve, it is evident that the surface area as determined by the turbidimeter affords a better criterion of the effects of fineness than the residue on the No. 200 sieve. Also the data shown in the lower part of the figure exhibit a more consistent relation to strength than do those plotted against the percentages passing the No. 325-mesh sieve in the upper part of the figure.

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* From data by H. J. Casey, *Jour. Am. Conc. Inst.*, Jan.–Feb., 1937, p. 279.

From the above it appears evident that a well-burned, finely ground cement can carry a greater proportion of sand than a more coarsely ground cement and will be more economical, provided the cost of the additional grinding does not offset the advantage derived.

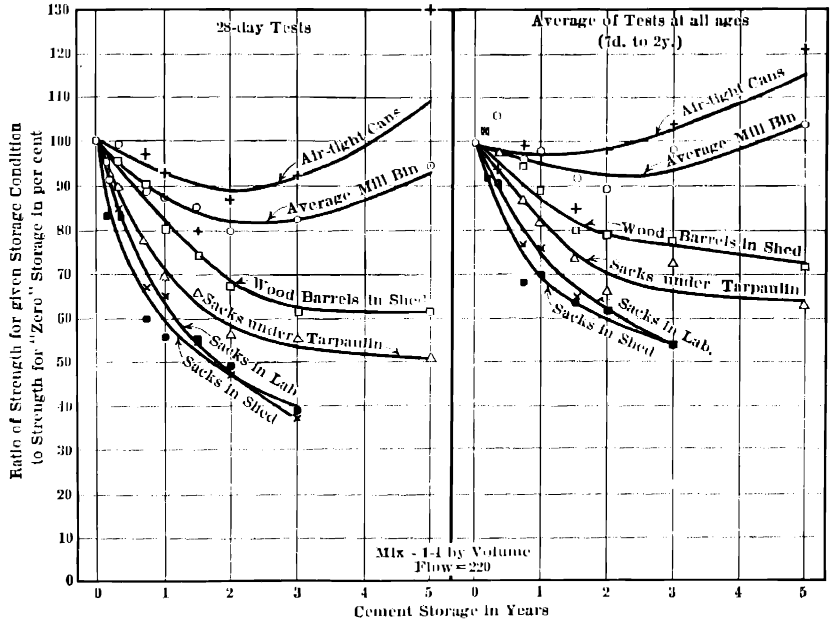

FIG. 11.—Effects of Storage of Cement on Concrete Strength. (Tests made at Portland Cement Association Laboratory.)

The amount of " seasoning " or aeration which the cement has received subsequent to final grinding influences markedly its strength.

The result of tests reported by the Director of Research of the Portland Cement Association, 1928, are shown in Fig. 11. These and other tests indicate that cement can be kept indefinitely in good condition in tight bins or cans but it deteriorates considerably when stored in sacks exposed to the air. During the exposures represented in Fig. 11, the moisture and carbon dioxide contents and the loss on ignition all increased with age and severity of the exposure. Thus cement stored in sacks in a shed for 3 years carried 2.5 per cent CO_2, 1.1 per cent H_2O, and 5.3 per cent loss on ignition, whereas the corresponding quantities for cement stored in mill bins were 0.4, 0.3, and 1.2 per cent, respectively. Hence a high loss on ignition is one index of long storage.

Many tests have been made to determine the effect of the percentage of mixing water upon the strength of cement mixes. Data for concrete tests showing the relation of the strength to the water-cement ratio appear in Art. 511. For purposes of testing the strength of cement, use is made of mortars containing standard Ottawa sand passing a 20-mesh and held on a 30-mesh sieve, or a more finely graded variety of this sand. A plastic consistency determined as indicated in Art. 417 is used in making standard sand mortars of 1 : 3 proportions, by weight. Such mortars will show a flow between 35 and 60 per cent when given twenty-five ½-in. drops in 15 sec. on a 10-in. flow table (Art. 447). With the methods of hand mixing and molding standard in the United States, the use of such consistencies promotes optimum strengths and minimum deviations from strength averages. Recently a wetter consistency having a flow of 100 to 130 per cent has been used as a means of standardizing cement strength in compression. In the latter case the mortars are made of finely graded Ottawa sand in 1 : 2.75 proportions, by weight, with water equal to 53 per cent of the weight of the cement. Since changes of 1 per cent in the amount of mixing water are likely to reflect somewhat greater inverse changes in strength, the water must be accurately weighed.

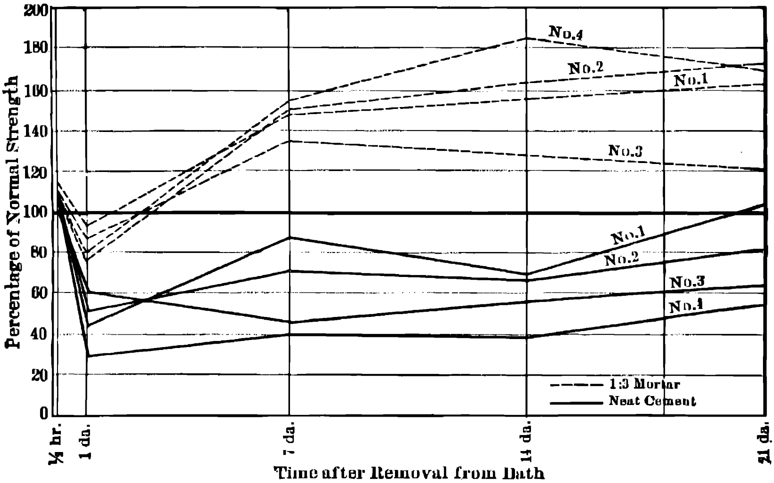

FIG. 12.—Effects of Drying on the Tensile Strengths of Neat and 1 : 3 Standard Sand Mortars. Age at removal from bath was 28 days; 4 tests per point.

If briquettes are removed from water before testing, a considerable effect, dependent upon the time they dry, may be produced upon their strength. Figure 12 has been compiled from the results of experiments by A. J. Barclay,* on four different brands of cement. Similar tests have been reported by Prof. J. L. Van Ornum in *Eng. News*, Vol. 51, p. 24, and by Prof. R. P. Davis in *Eng. News*, Vol. 61, p. 581.

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* Thesis, University of Wisconsin, 1912.

352. Conditions Affecting the Time of Set.—The factors which influence the setting properties of the cement are its composition, the percentage of retardant, degree of calcination, fineness of grinding, aeration subsequent to grinding of clinker, percentage of water used in gaging the paste, the temperature of the mixing water and cement, the humidity and temperature of the moist closet or of the atmosphere in which the cement paste is placed, and the amount of manipulation the paste receives.

The effect of lime, silica, and alumina in controlling the set have already been referred to in Art. 330. Although the proportion of these oxides exercises a marked influence on set, nevertheless finely ground clinker sets too quickly when mixed with water; hence some provision must be made by the manufacturer to increase the time of setting of freshly ground cement so that it will be sufficiently slow-setting for use in construction. This is commonly done by mixing gypsum ($CaSO_4+2H_2O$) or plaster of Paris ($CaSO_4+\frac{1}{2}H_2O$) with the clinker before final grinding, or by adding one of these compounds just after the clinker has received preliminary grinding. Although these methods are manifestly imperfect since it is impossible to obtain an absolutely homogeneous mixture with either, yet they are the best now devised. (The addition of gypsum before calcination causes it to decompose into lime and sulphur trioxide. Since the latter is liberated in the kiln the resulting effect on the time of set is nil.)

Experiments by Le Châtelier, and later ones by Meade and Gano,* have shown that anhydrous calcium sulphate, plaster of Paris, or gypsum may be used as the retardant. The experiments of Meade and Gano, however, indicate that increasing any one of these elements up to 2 or 3 per cent (the limit will vary with the chemical composition of the cement) retards the set but further additions of plaster of Paris cause the setting time to decrease. The introduction of 10 to 20 per cent of plaster of Paris will generally cause the cement to become quick-setting again. The latter effects were not observed in the tests made with gypsum ($CaSO_4+2H_2O$) or dead burned gypsum ($CaSO_4$).

In addition to the above-mentioned elements, small percentages of calcium chloride, aluminum chloride, magnesium chloride, sodium hydroxide, potassium hydroxide, sodium silicate, and sodium carbonate † also exercise a marked acceleration upon the setting properties of cement. Nihoul and Dufossez showed that strontium sulphate, barium sulphate, calcium sulphate, and calcium aluminate in small percentages also effected a rapid increase in set.

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* *Chemical Engineer*, Vol. 1, p. 92; see also the tests of Nihoul and Dufossez, abstracted in *Jour. Soc. Chem. Industry*, Vol. 21, p. 859.

† *Concrete-Cement Age*, November, 1912, p. 68.

Often an underlimed cement will become quick-setting after seasoning. This fault can be overcome by increasing the lime content in the raw materials or the remedy mentioned below may be applied to the cement. Examples of cements which become slower setting with age are common, and some cases have been cited where cements slow-setting when fresh have become quick-setting and then slow-setting after aging for some time. Quick-setting may often be avoided by adding to the cement 1 or 2 per cent of hydrated lime or the fraction of a per cent of plaster of Paris.

TABLE 1.—INFLUENCE OF FINE GRINDING UPON THE INITIAL SET OF CEMENT (MEADE)

Per Cent Passing a No. 200 Sieve.	Setting Time in Minutes of Cement No.							
	1	2	3	4	5	6	7	8
75	255	105	120	240	240	200	100	115
80	246	106	115	200	210	190	100	105
85	192	100	100	180	110	175	90	100
90	75	100	95	115	55	100	80	75
95	12	22	60	60	15	25	25	30
100	2	6	35	30	5	2	5	10

The fineness to which a cement is ground produces an effect upon its time of set as the results in Table 1 * indicate. In general, it may be said that the more finely the cement is ground the more rapidly will it set. However, the relation between time of set and fineness as measured by the 200-mesh sieve is not rectilinear as inspection of the table will show. The results also indicate that grinding to a fineness of 90 per cent through the No. 200 sieve does not decrease the time of set below the customary limits.

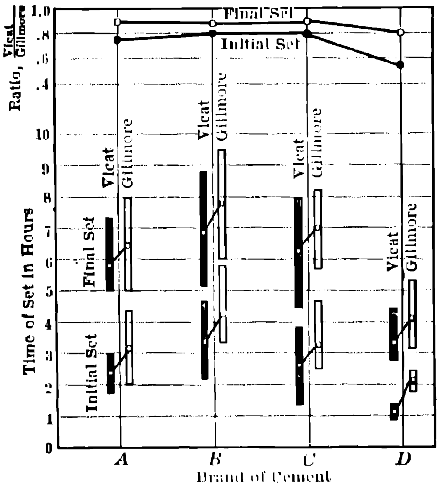

FIG. 13.—A Comparison of Gillmore and Vicat Determinations on Time of Set.

An increase of 1 per cent in the amount of mixing water used in testing cement pastes above that required for normal consistency may cause an increase of a half hour or more in either initial or final set. A comparison of Gillmore and Vicat methods is shown in Fig. 13, compiled from the

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* From a paper by Meade, *Proc. A.S.T.M.*, Vol. 8, p. 410.

Report of Committee C1 of the A.S.T.M. for 1930. These data represent the range in results from four laboratories operating on each of the four cements. The results show that the Vicat method indicates lower times of set than does the Gillmore. The ratios at the top of Fig. 13 indicate that the discrepancy is likely to be greater for a quick-setting cement like D than for a slower setting cement like B.

The influence of temperature upon the time of set is shown in Table 2. Cements stored in warm rooms will, in general, be quicker setting than those stored in a cold atmosphere. Cold mixing water retards set while warm water accelerates it. For the range of temperature ordinarily met in the laboratory say 65° to 75° F., the effect is not very marked. However, due consideration of the influence of temperature should be given in reporting on cements which are quick-setting in a hot laboratory but which will be used in a colder atmosphere.

TABLE 2.—INFLUENCE OF TEMPERATURE ON THE SETTING OF PORTLAND CEMENT †

Sample No.	Initial Set in Minutes. Temperature ° F.				Final Set in Hours. Temperature ° F			
	100	80	60	40	100	80	60	40
1	1½	4	6	13	1¼	1	2	2½
2	3	5	6	8	1	1¼	1¾	2½
3	4	10	15	20	½	¾	1½	6½
4*	5	9	15	30	½	¾	1	6
5	6	10	14	25	1	1½	2	2½
6*	7	12	15	20	1¾	2	2¼	2½
7*	9	10	15	17	3½	6	7	12
8	10	15	35	40	¾	1	1¼	1¾
9	11	15	20	57	3	5	6	10
10	11	13	15	30	2½	3	3½	6
11	19	32	60	120	3	6	7	15
12	15	35	70*	360	3½	6	7	22

* Contain a considerable admixture of Kentish Rag.
† From Butler's *Portland Cement*, p. 267.

Cements exposed to a thoroughly saturated atmosphere will set much more slowly than those exposed to a dry atmosphere. If, however, a considerable proportion of moist CO_2 is present in the air, the experiments of Gadd * seem to indicate that the setting time will be greatly reduced.

By lengthening the time of mixing and by prolonged troweling of the surface mortars it is also possible to considerably delay the time of set.

353. Conditions Affecting Fineness.—The percentage of flour contained in a cement is principally dependent upon a number of variables in the method of manufacture. The chemical composition and the degree of calcination influence the hardness of the clinker and consequently affect the fineness to which the clinker is ground. Clinker high in iron or silica is apt to be hard and difficult to grind. The same is true of a hard-burned clinker. It does not always follow, therefore, that a difference in fineness indicates the relative quality of two cements since the one more finely ground may have been underburned. Furthermore, the fineness will be influenced by the time of grinding and the character of the pulverizing machinery employed in grinding.

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* See *Cement Concrete Age*, Cement Mill Section, Feb., 1914; also paper by G. M. Williams, *Proc. A.S.T.M.*, Vol. 14, p. 174.

To some extent seasoning also affects fineness. It has been found that cement becomes slightly finer with age provided it does not absorb too much moisture. This is probably due to the decrepitation of the coarser grains resulting from hydration of the embedded lime particles.

Methods for testing the fineness of cement, and the errors in sieves are discussed in Art. 410 to 413.

354. Conditions Affecting Specific Gravity.—In the majority of cases, the specific gravity affords little if any information concerning the relative value of two cements made from different materials, unless the average specific gravity of each brand is known. The test is chiefly used to detect abnormal conditions in a brand of known specific gravity.

The detection of adulteration by this test is dependent upon the specific gravity of the adulterant and upon the proportion used. A simple computation reveals that a clinker having a specific gravity of 3.15 may be adulterated with 14.3 per cent of limestone having a specific gravity of 2.8 before the specific gravity of the mixture will be reduced below the normal minimum usually taken as 3.10. If, instead, of limestone, a blast-furnace slag or natural cement with a specific gravity of 3.0 be employed, 6.7 per cent of the adulterant may be used before the specific gravity of the adulterated cement is reduced 0.01. Furthermore, it is permissible under the above methods of testing to ignite the sample if its specific gravity falls below 3.10. Experiments have shown that this procedure will raise the specific gravity of many adulterated mixtures considerably above the specified limit. So it is evident that, although adulteration lowers specific gravity, a low result is not necessarily a sign of adulteration, nor is a high value an indication of the absence of it.

Long seasoning is the chief cause of a low specific gravity in an unadulterated cement. This is due to the fact that freshly ground cement when exposed to the air rapidly absorbs moisture and carbon dioxide. A month's seasoning will often reduce the specific gravity from 3.15 to 3.08, or thereabouts, and a long period of seasoning may reduce it to 3.00.* Drying seasoned samples at 212° F. will slightly raise the specific gravity while igniting will, in general, raise the specific gravity to the original value. Seasoning the clinker lowers specific gravity.

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* For example see *Chem. Engr.*, Vol. 6, p. 19; or Taylor's *Practical Cement Testing* p. 48.

The chemical composition of a cement also affects its specific gravity. Cements with high contents of iron oxide will have specific gravities 0.05 to 0.10 higher than those with low iron contents, provided both have been subjected to similar storage conditions.

Formerly the degree of calcination was supposed to affect the specific gravity, but numerous experiments have completely disproved this theory.* The effects of fineness of grinding upon specific gravity are slight. Very finely ground cements on account of the readiness with which they absorb moisture and carbon dioxide are likely to have lower specific gravities than cements made from the same materials but more coarsely ground.

RESULTS OF VARIOUS TESTS ON PORTLAND CEMENT

355. General.—We shall now consider some results of tests on Portland cement pastes and standard sand mortars. Only those results which are especially affected by the cement itself will receive attention herein. The effects produced upon mortars by variables in the aggregate will be considered in Ch. XIV.

356. Strength Tests.—Strength-age curves for 1 : 3 standard Ottawa sand mortars of standard consistency and similar curves for 1 : 2.75 mortars made of graded Ottawa sand with a water-cement ratio of 0.53, by weight, are shown in Fig. 14 for seven normal Portland cements and in Fig. 15 for five high-early-strength Portland cements. These data were taken from the tests of Committee C1 reported in *Proc. A.S.T.M.*, Vol. 1, 1934, p. 322. Each point for a given curve represents the average of 120 tests made in 10 laboratories. The compositions of these cements are given in Table 3 and physical properties in Table 4. From the average curves shown in the lower part of Fig. 15, one obtains a good comparison of the early compressive strengths of normal and high-early-strength Portlands. Figure 16 shows average strength-age curves for compressive and bending strength tests of four types of cement differing in C_3S and C_2S contents. The Cowe Bay sand used in most of these tests was a well-graded quartz sand. It passed a No. 4 sieve, had 49 and 96 per cent retained on the No. 28 and 100 sieves, respectively. Its fineness modulus was 2.7. The water-cement ratio for the 1 : 2 mortars averaged 0.43 and for the 1 : 4½ mortars 0.40, by weight.

These data show, as do those of Fig. 7, that, although cements high in C_3S exhibit the highest early strengths, those of lower C_3S and higher C_2S contents show the highest strengths after a year or more of moist curing.

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* See *Chem. Engr.*, Vol. 6, p. 17; and *Proc. Inst. of Civil Engr.*, Vol. 166, p. 342.

The data in **Fig. 17** (page 336) show ten-year tests of mortars of standard consistency made with four cements commonly used in the middle west in 1923. These cements were not so finely ground as the normal

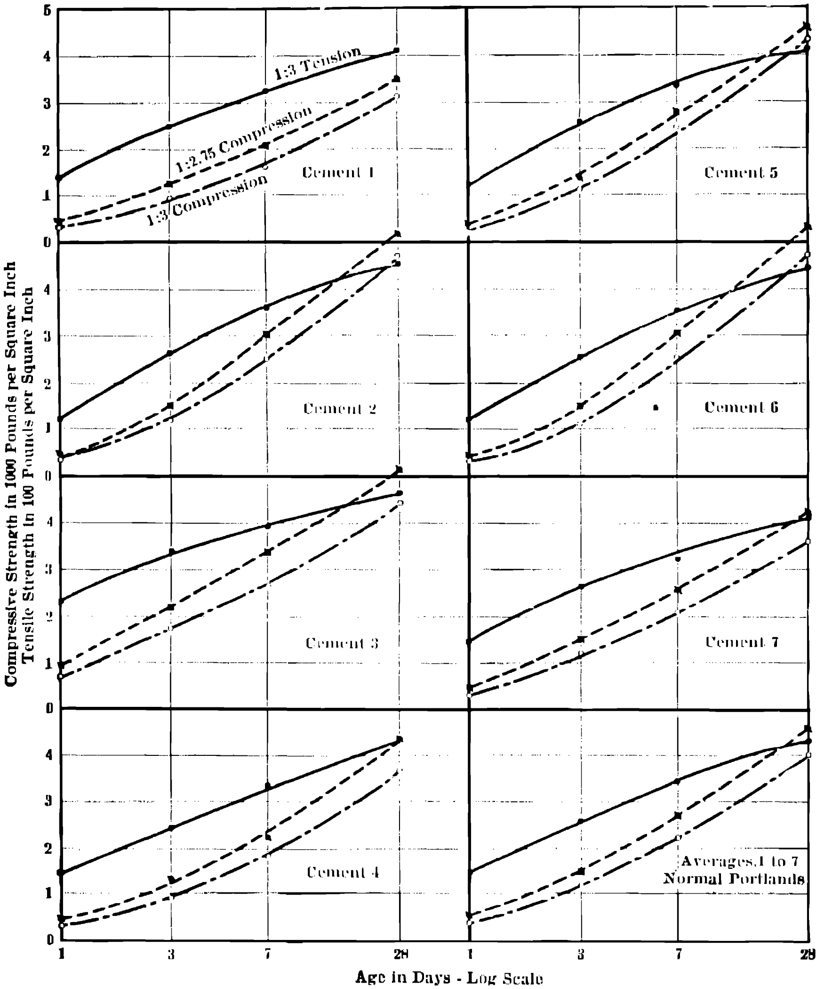


FIG. 14.—Strength-Age Curves for Standard Sand Mortars of Normal Portland Cements.

Portlands of today and in composition would now be classed as low in C_3S. They all exhibit satisfactory gains in mortar compressive strengths. Cured outdoors under an average humidity of 70 per cent, after an initial 28-day period in water, the 1 : 3 mortars at 10 years were 44 to 96 per cent stronger in compression than similar mortars cured continuously in water

Cured in water the tensile strengths of the mortars, Fig. 17, show retrogressions which are less pronounced in the specimens of graded

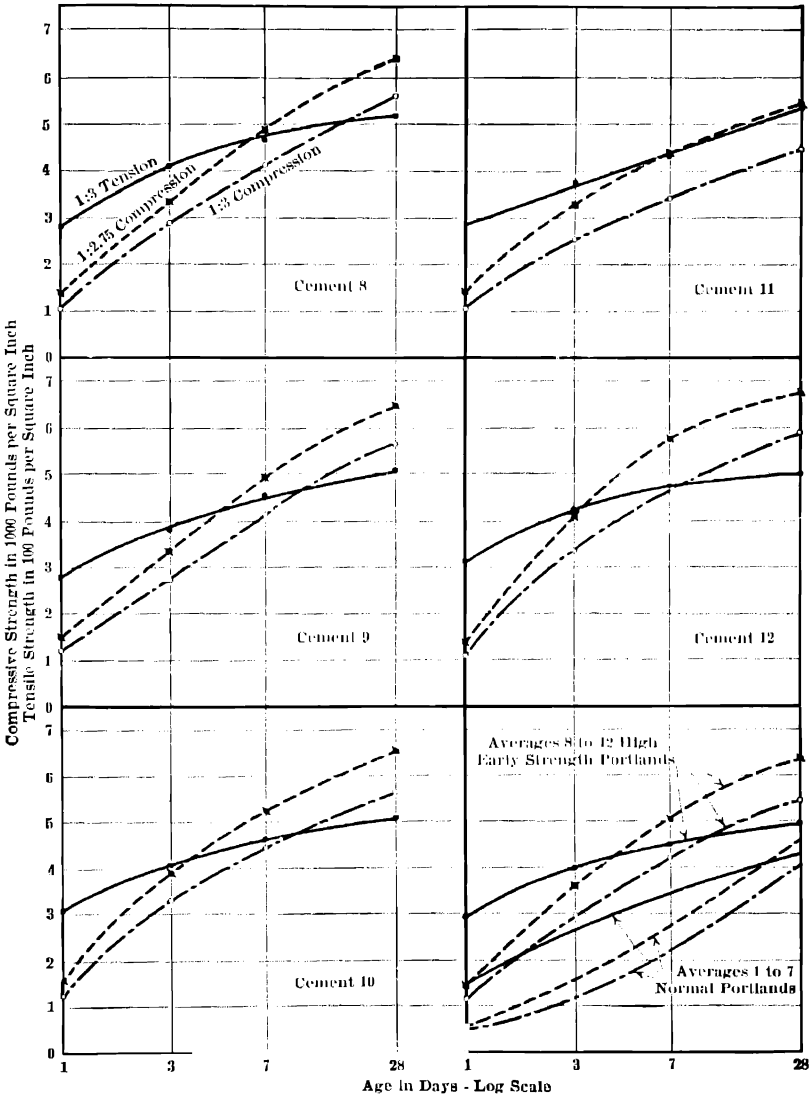


Fig. 15.—Strength-Age Relations for Standard Sand Mortars of High Early Strength Portland Cements.

Janesville sand and in specimens cured outdoors. Neat cement briquettes of these cements cured outside were in many instances cracked and exhibited tensile strengths of only $\frac{1}{10}$ to $\frac{1}{3}$ of the 28-day strength, whereas water-cured neat cement briquettes at 10 years exhibited strengths averaging from 505 for cement 5M to 775 lb./in.^{2} for cement 3M. In compression the 2 by 4-in. neat cement cylinders cured outside averaged between 10,210 for cement 5M and 16,455 lb./in.^{2} for cement 4M.

TABLE 3.—CHEMICAL COMPOSITION AND COMPUTED COMPOUND COMPOSITION FOR CEMENTS 1 TO 12
(See Figs. 14 and 15.)

Cement	Oxide Analysis, percentage by wt.						Loss on Ignition	Insoluble Residue	Computed Compound Composition Calculated to Clinker Basis, percent			
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3			C_3S	C_2S	C_3A	C_4AF
	Normal Portland Cements											
1	20.91	3.00	5.20	63.69	3.02	1.61	1.58	0.19	60	18	9	10
2	21.21	2.57	5.26	63.52	4.20	1.52	0.88	0.12	56	21	10	8
3	21.13	3.02	3.96	65.05	3.20	1.48	1.36	0.19	72	9	6	10
4	20.98	2.98	5.65	63.91	2.14	1.34	1.83	0.08	58	20	11	10
5	21.00	2.31	6.12	64.44	2.08	1.52	1.42	0.16	57	21	13	8
6	20.32	3.31	5.64	64.78	2.50	1.14	1.49	0.10	66	11	10	11
7	20.45	4.16	6.28	64.42	1.32	1.48	1.15	0.20	57	18	10	13
	High Early Strength Cements											
8	19.91	4.30	5.99	64.03	1.47	2.46	1.18	0.20	59	16	9	14
9	19.87	2.76	6.05	65.35	1.40	2.34	1.73	0.27	68	9	12	9
10	19.63	3.55	6.33	63.13	2.44	2.37	1.42	0.19	57	17	12	12
11	20.34	2.75	5.11	64.93	1.28	2.09	1.96	0.18	68	12	10	9
12	19.74	2.25	5.52	65.81	2.03	2.17	1.22	0.12	76	3	12	7

In conclusion, we may say for cements low in C_3A that C_3S exercises a marked influence on rate of increase in strength of moist-cured mortars up to 1 year; thereafter the effect of C_2S is more potent. The compressive strengths of mortars generally show an upward trend for ages beyond 1 year, but the tensile strengths often show retrogression. Retrogression in tensile strength is most pronounced in mixes rich in cement which are subjected to periods of wetting and drying, and in lean porous mixes which are stored continuously under water. Curing at low humidities is detrimental to strength of all mixes. Curing 1 : 3 mortars of standard sand in

TABLE 4.—AVERAGES OF PHYSICAL PROPERTIES OF CEMENTS 1 TO 12
(All cements were sound in pat tests.)

Cement No.	1	2	3	4	5	6	7	8	9	10	11	12
Water (per cent)	23.9	25.4	26.3	23.7	23.5	24.7	22.4	26.8	25.6	27.0	25.7	24.9
Initial Set,* h.m.	4:12	4:36	3:42	3:22	3:38	4:24	4:06	3:07	2:37	1:34	3:23	4:24
Final Set,* h.m.	6:31	7:02	5:51	5:58	5:29	6:32	6:25	5:18	4:34	5:14	5:14	7:22
Per cent Passing No. 200 Sieve	93	95	98	98	89	96	92	100	99	100	99	98
%<11 microns	28	27	43	36	27	31	31	46	43	48	39	39
%<21 "	45	45	66	54	42	48	44	60	61	73	61	60
%<31 "	62	66	84	73	60	68	62	89	79	91	83	79
%<44 "	71	76	90	82	68	78	71	94	88	97	91	86
Surface Area cm^2/gm.	1520	1530	2130	1830	1470	1660	1600	2230	2070	2320	2000	1970
* Gillmore Method.	← Normal Portlands →							← High Early Strength →				

moist air usually produces lower strengths than curing in running water at ages up to six months, but subsequently the specimens cured in moist air become stronger.

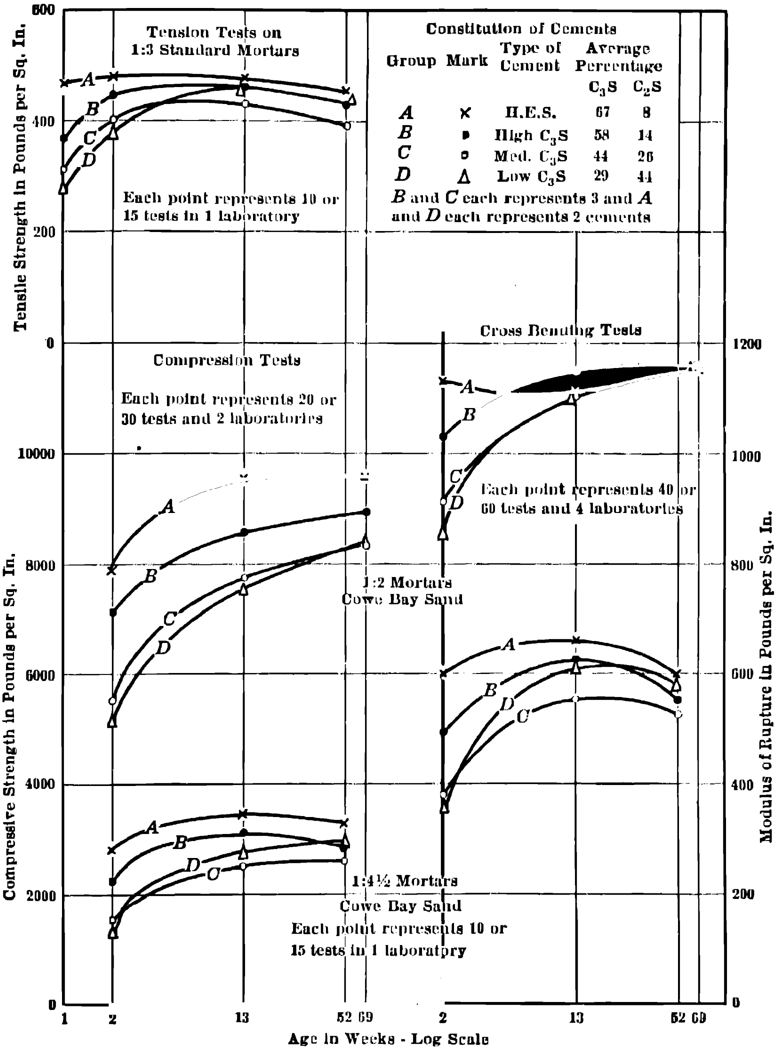
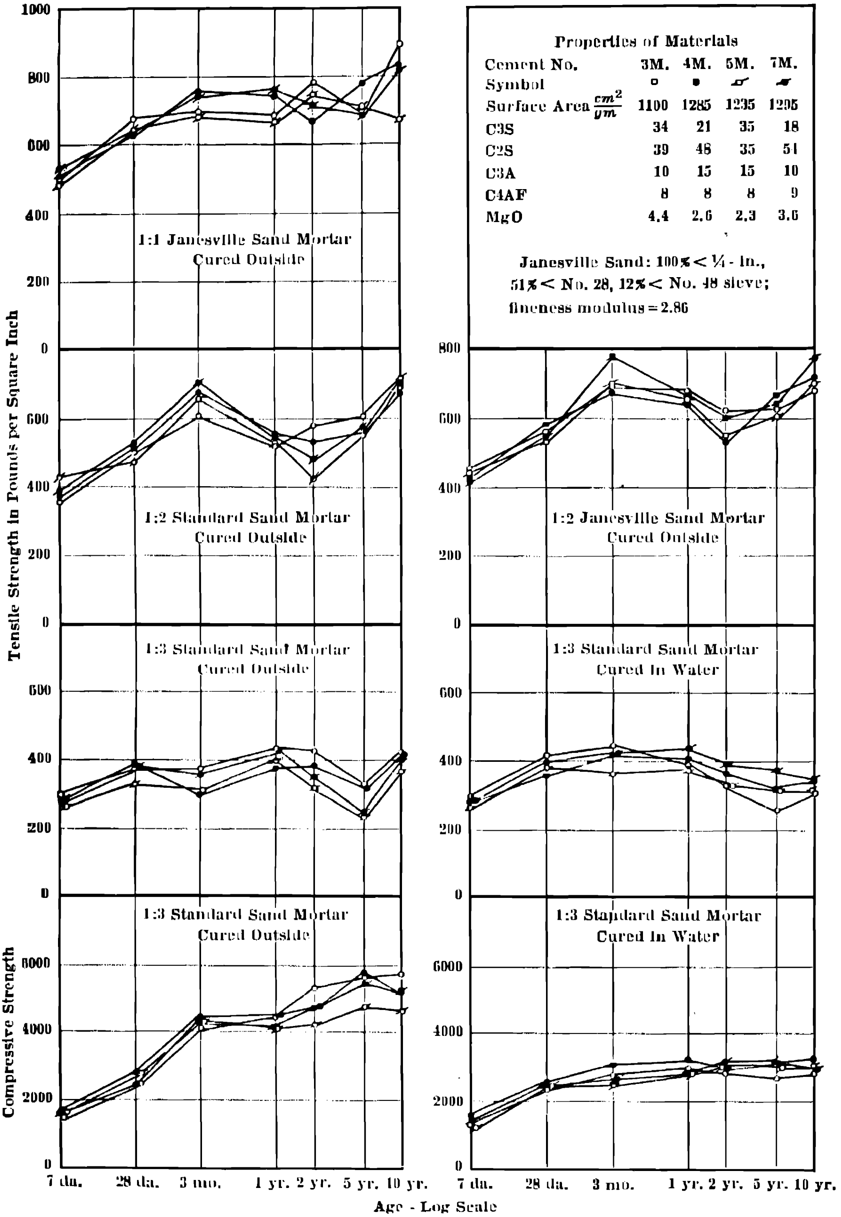


FIG. 16.—The Influence of Compound Composition on Mortar Strength. (Compiled from *Proc. Highway Research Board*, Vol. 16, 1936, p. 135.)

367. Expansion and Contraction Due to Variations in Moisture Content.—Owing to colloidal nature, Portland cement pastes and mortars undergo a volumetric contraction when they are allowed to dry in air and to a less extent an expansion when hardened in water.



Properties of Materials

Cement No.	3M.	4M.	5M.	7M.
Symbol	○	●	□	■
Surface Area $\frac{cm^2}{gm}$	1100	1285	1235	1295
C3S	34	21	35	18
C2S	39	48	35	51
C3A	10	15	15	10
C4AF	8	8	8	9
MgO	4.4	2.6	2.3	3.6

Janesville Sand: 100% < ¼ - in., 51% < No. 28, 12% < No. 48 sieve; fineness modulus = 2.86

FIG. 17.—Strength-Age Curves for Mortars of Four Portland Cements. (Wisconsin Tests.)

The contraction in air varies with the decrease in the proportion of free water in the pores plus water held in the colloids.* It may be increased

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* Y. Yoshida, *Jour. Am. Conc. Inst.*, Vol. 9, No. 1, 1937.

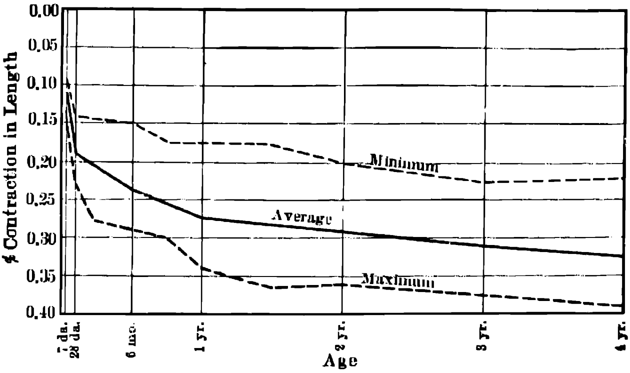


FIG. 18.—The Linear Contraction of Prisms of Neat Cement Stored in Air. (White.)

by the water released by carbonation of calcium hydroxide. The expansion in wet curing is dependent upon the increase in the proportion of water combined with the cement.

The existing evidence shows that both hygral expansion and contraction vary with the paste content of the mix and with the ratio of water to the cement. The contraction in air varies with (1) the humidity of the surrounding atmosphere, (2) the ratio of the exposed surface to the volume, (3) the thickness of the mortar or concrete, (4) the proportion of cement grains hydrated, which is largely dependent on the length of the moist curing period, (5) the length of the drying period, and (6) the proportion of tricalcium aluminate in the cement.

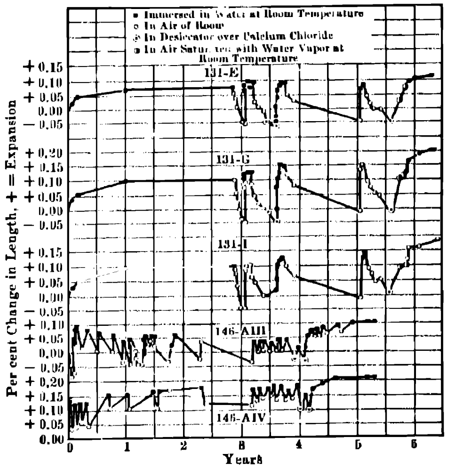


FIG. 19.—Changes in Length of Neat Cement Bars when Alternately Wet and Dried at Room Temperature. (White.)

A summary of important experiments by Prof. A. H. White is given in *Proc. A.S.T.M.*, Vol. 11, p. 531 and Vol. 14, p. 204. All cements used by White passed the standard soundness tests. After being cured 24 hours in moist air, the initial readings were taken on the 1 by 1 by 4-in. prisms, a micrometer with probable error of 0.003 per cent being used.

Figure 18 shows the average contraction of air-cured neat cement prisms at various ages up to four years. Five or six different brands are represented up to two years, and three brands for the remainder of the time period. The effect of prolonged seasoning on contraction was negligible.

Figure 19 gives the expansion time curves for water-cured neat prisms made of four brands of cement and also shows the effects of removal from water and subsequent immersion. It will be noted that the bars shrank very slowly after removal from water but expanded very rapidly within a day when subsequently immersed. The behavior of the duplicate bars 146A3 and 146A4 well illustrate this phenomenon. The former, after being subjected to short immersion periods and long drying periods, exhibited no pronounced change in mean length during three years' treatment, whereas bar 146A4, which received long periods of soaking and short-drying periods, increased in mean length about 0.15 per cent during the same time. No diminution in the proportionate expansion or contraction of the bars appeared after repeated applications of the wetting and drying process. In several instances the changes in length increased with repetitions of this treatment. A saturated atmosphere caused expansion comparable to that obtained by immersion in water.

Alternate wetting and drying caused more rapid changes in 1 : 3 mortar specimens than in those made of neat cement. Prisms cut from sound and strong sidewalk tops, which had seen twenty years' service, exhibited changes in length similar in kind and intermediate in magnitude to the changes observed in the neat and mortar bars. Experiments on compound bars made of equal layers of neat cement and 1 : 3 mortar led White to the conclusion that such specimens expanded and contracted together but not at the same rate nor to the same degree, the difference in expansion varying from 0 to 0.15 per cent.

Table 5 gives average values of expansions obtained by the U. S. Bureau of Standards Laboratory for neat and 1 : 3 mortar prisms made from ten different American brands of Portland cement.

TABLE 5.—AVERAGE LINEAR EXPANSION OF NEAT AND 1 : 3 STANDARD SAND MORTAR PRISMS OF TEN DIFFERENT BRANDS OF PORTLAND CEMENT CURED IN WATER

(*Proc. A.S.T.M.*, Vol. 15, p. 141.)

Mix.	Percentage Linear Expansion at Thirteen Weeks.*					
	Normal Cement			Reground 87–93% <No. 200 Mesh.		
	Maximum	Minimum.	Average.	Maximum.	Minimum.	Average.
Neat	0.120	0.057	0.066	0.132	0.056	0.085
1 : 3	0.024	0.005	0.012	0.027	0.005	0.013

* Average results represent twenty specimens. Each specimen was measured several times with a Barry strain gags.

A comparison of the contractions of $1\frac{1}{2}$ by $1\frac{1}{2}$ by 12-in. bars due to variations in paste content is well shown in Fig. 20 from the tests by Y. Yoshida.

The effect of tricalcium aluminate on expansion of cement mortars was reported by Gonnerman (refer to Art. 351). Length measurements were made on 3 by 3 by 15-in. mortar bars of 1 : 3.6 proportions, by weight. He found that the contraction after 2 yr. in air at 50 per cent relative humidity and room temperature, following 3 mo. of moist curing, varied from 0.07 per cent for mortars with cements having no tricalcium aluminate, C_3A, to 0.11 per cent for others having a C_3A content of 20 per cent. The contractions after moist curing 7 days and drying 14 mo. were approximately the same. His data indicate that the contraction caused by tricalcium aluminate was proportionately three times as much as that due to C_2S or C_3S.

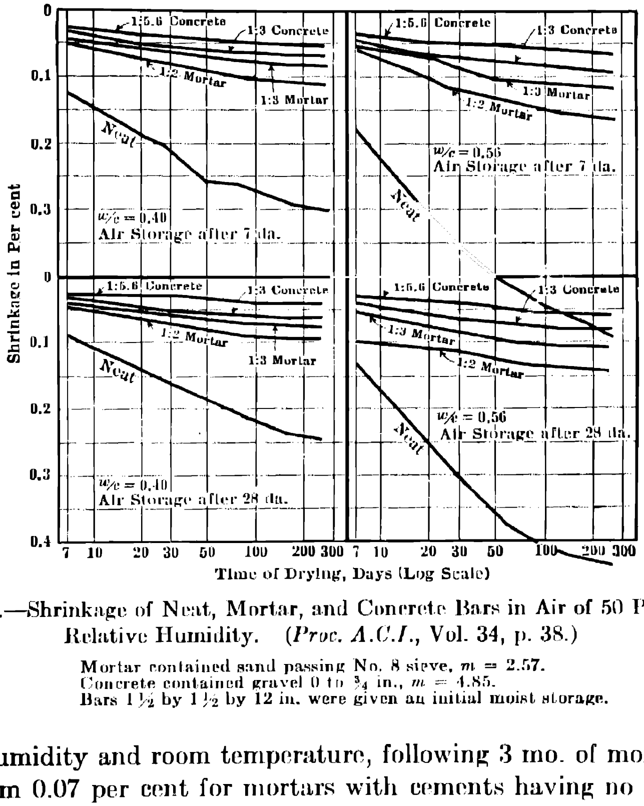


Fig. 20.—Shrinkage of Neat, Mortar, and Concrete Bars in Air of 50 Per Cent Relative Humidity. (*Proc. A.C.I.*, Vol. 34, p. 38.)

Mortar contained sand passing No. 8 sieve, $m = 2.57$.
Concrete contained gravel 0 to $\frac{3}{4}$ in., $m = 4.85$.
Bars $1\frac{1}{2}$ by $1\frac{1}{2}$ by 12 in. were given an initial moist storage.

For data on hygral changes of concrete see Art. 522.

358. Effect of Remixing and Retempering on Strength of Cement.—From the results of tests made at the Watertown Arsenal there has been plotted Fig. 21. This diagram shows the strengths of 6-in. neat cement cubes made from pastes which were remixed by hand after setting for

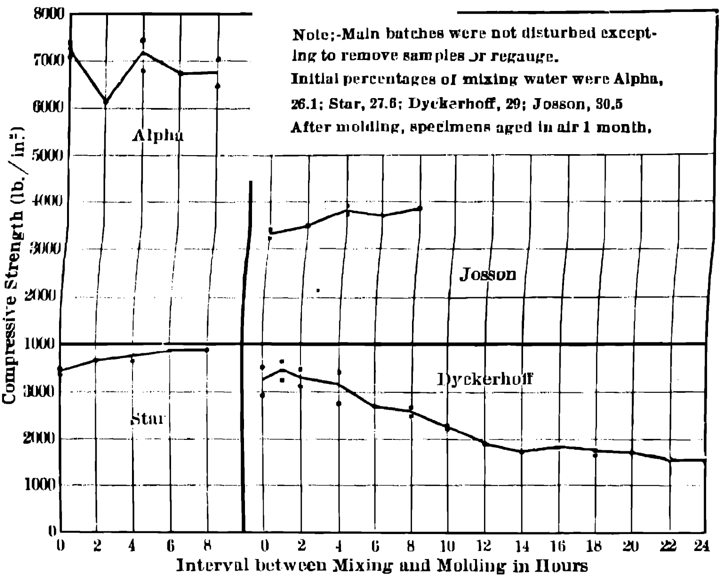


FIG. 21.—Effect of Remixing after Setting upon the Compressive Strength of Neat Cement Cubes.

different intervals of time. The initial percentage of water is indicated in the figure. Sufficient additional water was added whenever the paste became dry to secure the original consistency.

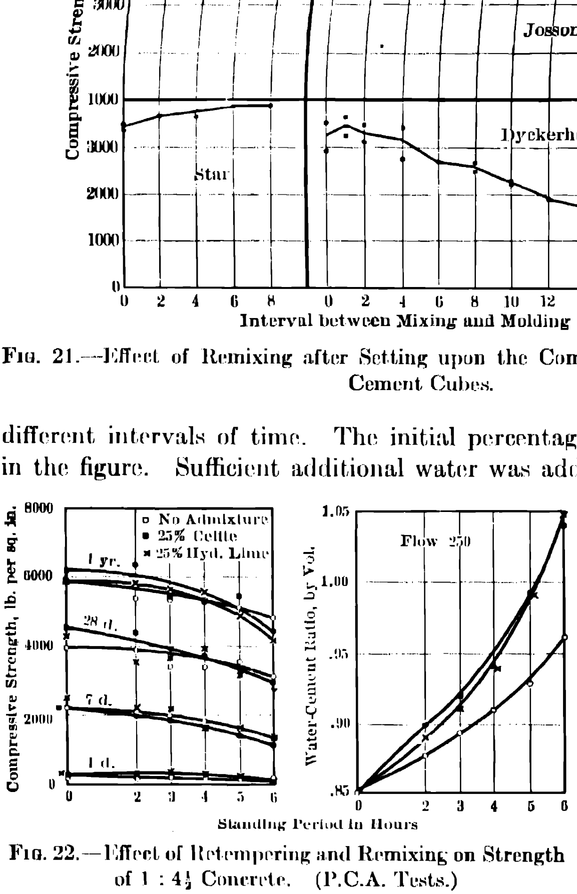


FIG. 22.—Effect of Retempering and Remixing on Strength of 1 : $4\frac{1}{2}$ Concrete. (P.C.A. Tests.)

The influence of retempering and remixing of concrete mixes of 1 : $4\frac{1}{2}$ proportions, by volume, with and without admixtures is shown in Fig. 22, from the Report of the Director of Research of the Portland Cement Association. These data indicate that the strength was reduced in proportion to the increase in the water-cement ratio caused by retempering. After standing 6 hr. the compressive strength of the retempered mixes without admixtures was reduced 15 to 20 per cent. When no retempering was done, the strengths were not materially affected by standing 6 hr., but the workability as expressed by the flow was reduced from 250 to 160 per cent.

Table 6 shows the strengths at one month of grouts made from various cements which were allowed to remain for 15 or 16 hr. in the mixing board and were then remixed with an addition or removal of water, if necessary, to obtain the consistency ordinarily used by masons.

TABLE 6.—EFFECT OF RETEMPERING ON THE COMPRESSIVE STRENGTH OF NEAT CEMENT GROUTS *

Specimens were 6-in. cubes. Age at test = 1 mo.

Brand.	Kind of Cement.	Per Cent Water (by Wt.) at		Interval between Mixing and Molding (Hr.).	No. of Spec.	Compressive Strength (Lb. per Sq. In.)		
		Mixing.	Molding.			Max.	Min.	Average.
Alpha......	Portland	44.9	43.9	15	8	3706	3302	3480
Dyckerhoff.	Portland	43.3	43.3	15	8	2250	1908	2113
Josson.....	Portland	48.6	43.7	15	8	2304	1976	2087
Steel.......	Slag	50.9	50.9	15	8	585	519	554
Mankato...	Natural	68.8	68.8	16	7	316	255	294
Norton.....	Natural	59.0	64.5	15	8	377	305	343

* *Tests of Metals*, 1901, p. 520.

359. Effects of Low Temperatures on the Strength of Cement.—In general it may be stated that the setting of cement proceeds at a very slow rate when the temperature falls below 40° F. When the temperature falls below freezing the particles of cement in unset specimens are separated by the expansion of water in freezing. A minimum amount of water should, therefore, be used in cement work subjected to freezing temperature in order that this expansive action may be as small as possible. Alternations in freezing and thawing before the cement has attained hard set generally cause a loss in cementing power owing to the repeated breaking of the bond between adjacent particles. If the work freezes before setting but thaws without refreezing, it will in time secure 50 per cent of normal strength if moisture is provided for proper curing.

From the result of a very large number of compression tests on neat cement made at the Watertown Arsenal, the data in Table 7 have been selected. These tests show that there is considerable chemical activity in neat cement when setting at 0° F. It appears that neat cement specimens subjected to such low temperatures immediately after mixing gain strength at a very much slower rate than specimens cured at room temperatures; but that after several years the test-pieces stored at low temperatures develop a considerable proportion of their normal strength. It also appears that specimens hardening at 70° F. for a given period will attain a greater strength than specimens which are allowed to harden for a like period after an exposure to freezing temperatures. If neat specimens are allowed to set for one day at room temperature before being subjected to freezing temperatures, the rate of growth in strength is more rapid than if immediately frozen.

TABLE 7.—THE EFFECTS OF LOW TEMPERATURES ON THE COMPRESSIVE STRENGTH OF 2-IN. CUBES OF NEAT PORTLAND CEMENT

(Tests of Metals 1901, 1902 and 1907.)

Brand of Cement.	Per Cent Water.	Time of Setting in Air at Temperatures of			Total Age. Days.	Compressive Strength * in Lb.-in.² After Storage.	
		70° F. Days.	0° F. Days.	70° F. Days.		Treatment Indicated.	In Air at 70° F for Total Age.
Star.........	23.4	0	31	1	32	1350	4570
		0	31	7	38	2340	4820
		0	89	1	90	1720	
		0	89	30	119	3620	4410
		0	1 yr.	1	.....	2724	
Star.........	24.0	0	5 yr.	1	.....	3250	
Alsen........	28.2	0	30	1	31	986	3900
		0	30	7	37	2440	3450
		0	90	1	91	1210	4040
		0	90	29	119	2520	3510
		0	1 yr.	1	.....	1580	
Alpha........	25.0	.....	.....	1	1	....	582
		1	7	1	9	2400	4990
		1	179	1	181	3670	5910
	25.0	1	5 yr.	1	.....	6320	
		1	5 yr.	36	.....	8100	
Alpha........	23.0	.....	.....	7	7	....	5550
		7	9	1	17	5160	5730
		7	188	1	196	5350	5940
		7	5 yr.	1	.....	7310	
		7	5 yr.	41	.....	7650	
Atlas........	24.0	.....	.....	1	1	....	689
		1	7	1	9	2140	4130
		1	181	1	183	2950	5410
		1	5 yr.	1	.....	4160	
		1	5 yr.	40	.....	6780	
Atlas........	24.0	.....	.....	7	7	....	3730
		7	7	1	15	4210	4890
		7	18	1	192	4500	5790
		7	5 yr.	1	.....	6640	
		7	5 yr.	40	.....	7410	

* Each result is averaged from five or more tests.

Tests on mortars and concretes indicate that high early strength Portland cements and cements high in tricalcium silicate have resistance to freezing and thawing superior to the modified cements or those low in tricalcium silicate. This is especially true if freezing takes place at an early age. A high tricalcium aluminate content also appears detrimental to resistance to freezing and thawing. For additional data on effects of low temperatures on concrete, see Art. 539.

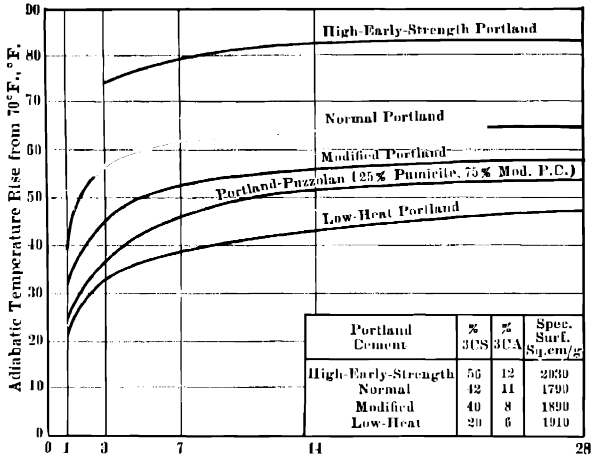
360. Effect of High Temperatures on the Strength of Neat Portland Cement.—In *Tests of Metals*, 1902, a report is made of a number of tests on 4-in. cubes of neat cement which were cured for one year in air or water and then gradually heated to temperatures of 600° to 1000° F. The cubes were cooled in asbestos or sawdust and aged for four days to four months before they were tested. After being heated most of the cubes showed faint cracks, which gradually enlarged when the cubes were allowed to stand in air for several days. In several of the specimens subjected to temperatures of 900° F. these cracks became so large that the specimens were rendered unfit for testing. Specimens subjected to temperatures of 800° F. or above showed a marked decrease in strength, especially those hardened in water. Of the cubes made from Dyckerhoff cement and gaged with 29 per cent of water, those hardened in air showed a loss of weight varying from 7.7 per cent after being subjected to 700° F. to 10.5 per cent after 1000° F.; those hardened in water lost 17.7 per cent after being heated to 1000° F.

361. Experiments on the Rise in Temperature during Setting.—In large masses of concrete the heat evolved in setting is dissipated so slowly that a marked rise in temperature occurs. Eventually the interior cools and contracts, thus inducing tensile stresses in the interior of the mass. If these are sufficiently high, they may cause cracks, which in turn may unite with surface shrinkage cracks and thus promote leakage and subsequent disintegration. Hence special attention is given to the selection of the cement, the proportioning of the mix, and the rate of placement for such structures. The average heats of hydration for various types of cement reported by the Bureau of Reclamation in *Special Cements for Mass Concrete* (1936) are:

Type of Cement	No. of Cements Averaged	Specific Surface Cm²/gm.	C_3S Per Cent	Heat of Hydration in Calories per gram of Cement after		
				3 days	7 days	28 days
High Early Strength.......	12	2030	56	102	108	114
Standard.................	11	1770	43	79	86	91
Modified.................	12	1930	42	63	74	82
Low Heat.................	14	1930	20	44	52	65

The computed relative effect of various types of cement on adiabatic temperature rise (no heat loss permitted) in concrete containing 1 bbl. of cement per cu. yd. is shown in Fig. 23.* For an initial temperature of 40° F., the rise above that initial temperature is less during the first few days, but at 28 days somewhat greater than for an initial temperature of 70° F.

Professor R. W. Carlson † has computed temperature rise in dams due to various rates of placement. Figure 24 shows the computed temperature rise at various distances above the foundation at the end of the 14th day after the initial lift was placed, when 5-ft. lifts were cast every 4 days. For 10-ft. lifts cast every 8 days, Carlson's computations indicate somewhat greater temperature rises. For 4 lifts of 2.5 ft. cast at 2-day intervals, the calculations show a maximum temperature rise of 24° F., as compared to 42° F. 4 days after placing a single 10-ft. lift. He indicates that less temperature rise will occur if a given height is placed in several small lifts and then time is allowed for the heat to dissipate prior to further placement.



Portland Cement	% 3CS	% 3CA	Spec. Surf. Sq.cm/g
High-Early-Strength	56	12	2030
Normal	42	11	1790
Modified	40	8	1890
Low-Heat	20	6	1910

FIG. 23.—Relative Effect of Type of Cement on Adiabatic Temperature Rise of Concrete. (J. W. Kelly.)

362. The Resistance of Cement to the Action of Alkali Waters and Sea Water.—Under laboratory conditions neat cement may be disintegrated by the combined chemical and mechanical action of waters containing various salts, such as the sulphates of magnesia and sodium, the chlorides of magnesia, sodium and calcium, and the carbonate of soda. The sulphates and chlorides are chemically active in removing lime from the cement, while the carbonate of soda alone or in solution with sodium sulphate or sodium chloride withdraws silica.* If the test-pieces are subjected to alternate wetting and drying a mechanical action greatly accelerates the breakdown of the cement. Under such conditions, crystals of large size are rapidly formed and expansive forces are produced. Under the action of these forces neat cement pastes are disintegrated more rapidly than lean mortars.†

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* From paper by J. W. Kelly, *Proc. Am. Conc. Inst.*, Vol. 34, p. 577.

† *Proc. Am. Conc. Inst.*, Vol. 34, p. 497.

In the investigation mentioned in Art. 351, Gonnerman reported tests of mortar briquets and cubes and 3 by 6-in. cylinders, the latter with a water-cement ratio of 0.56, by weight, all of which were subjected to the action of 2 per cent magnesium or sodium sulphate solutions after moist-curing for 28 days. The strength of the solutions was periodically adjusted to maintain constancy. From time to time, visual ratings of the appearance of the specimens were made, also strength tests. The data from Gonnerman's tests in Fig. 25 show that the resistance of the concrete specimens was lessened as the tricalcium aluminate content of the cement was raised above 7 per cent. Similarly he noted that the expansions of concrete cylinders subjected to sulphate attack became more pronounced when the C_3A content of the cement exceeded 7 per cent.

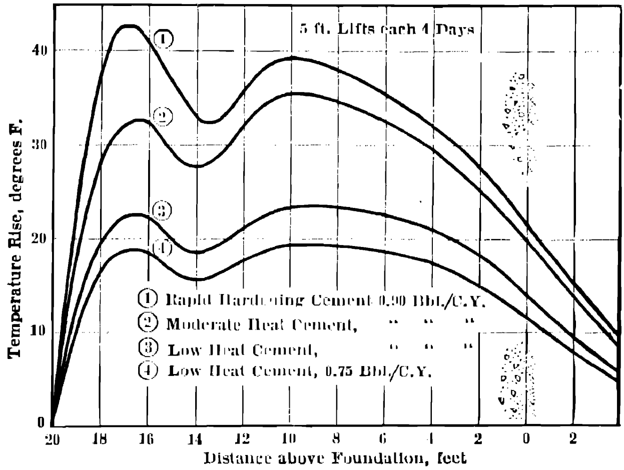

Fig. 24.—Calculated Temperature Distribution in a Mass of Concrete. (R. W. Carlson, *Proc. A.C.I.*, Vol. 34, p. 501.)

Stanton and Meder ‡ reported an extensive investigation by the

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* *Action of the Salts in Alkali Water and Sea Water on Cements, Technologic Paper*, No. 12, U. S. Bureau of Standards, by Bates, Phillips and Wig.

† *The Effect of Alkali Water on Cement Mortars*, A. J. Fisk, *Engr. News*, Aug. 18, 1910.

‡ *Proc. Am. Conc. Inst.*, Vol. 34, p. 433.

California Division of Highways on the resistance of cements to the attack of sea water and alkali soils. After analyzing soils and waters which had caused disintegration in concrete roads and structures, they subjected 6 by 6-in. cylinders of concrete containing 5 and 6 sacks of cement per cu. yd. to the action of the aggressive alkali soil. Specimens were moist-cured for 28 days and then buried to two-thirds their depth in pans of soil placed on the laboratory roof. In dry season tap water was added once or twice a week to maintain free moisture in the soil. The soils contained approximately 19 per cent of water-soluble salts, of which about $\frac{3}{4}$ was sodium sulphate and $\frac{1}{6}$ magnesium sulphate, the remainder of the salts being largely calcium sulphate, calcium chloride, and bicarbonate of soda.

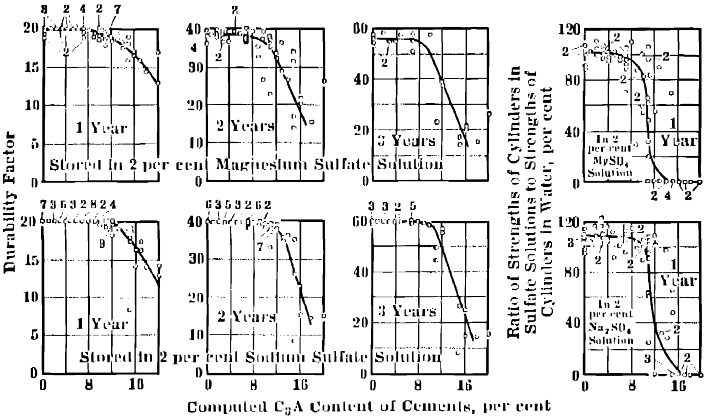

FIG. 25.—Influence of Tricalcium Aluminate Content of Cement on the Durability and Strength of Concrete Exposed to Sulphate Solutions. Numerals indicate number of identical values. (Gonnerman, loc. cit.)

The specimens were examined every three months and losses in weight determined.

Figure 26 shows the relation of the loss in weight to duration of exposure for cylinders of 5-sack concrete made with various standard and modified cements marketed in California. Of the modified cements ASW, BSW, and DSW were made by additions of iron or iron oxide to the raw mix prior to burning, thus reducing computed C_3A and increasing C_4AF. They were intended to be satisfactory for use in sea water and have moderate resistance to sulphate attack. Cements HSR and KSR with high iron contents were designed to have high resistance to sulphate attack. Cement LM was a puzzolan cement made by blending silicious material with the clinker. The advantage of this procedure arises from combination which this silicious material makes with any free lime in the clinker, thus forestalling the attack of the alkali sulphate on the free lime. These data show that the resistance to alkali attack is related to the computed content of tricalcium aluminate. With the exception of standard cements ES and ESW, the modified or blended cements, all of which were low in C_3A, were much more resistant than the standard Portland cements used in these tests. Cements ES and ESW were more resistant than their computed C_3A contents would indicate. This may have been due to conditions in manufacture which reduced the content of this component below the computed value.

363. Effects of Oils and Acids on Cement and Mortar.—Most mineral oils show no tendency to disintegrate well-cured cement mortars.* Lean mortars (1 : 4) may develop less strength when partially immersed in such oil after 7 days than when moist-cured for a month or more prior to immersion. Soaking the surface of a floor in a mineral oil of low viscosity will cause a marked reduction in its abrasive resistance. When mineral oils are incorporated into the mixing water they materially retard the set of the cement and reduce the strength.

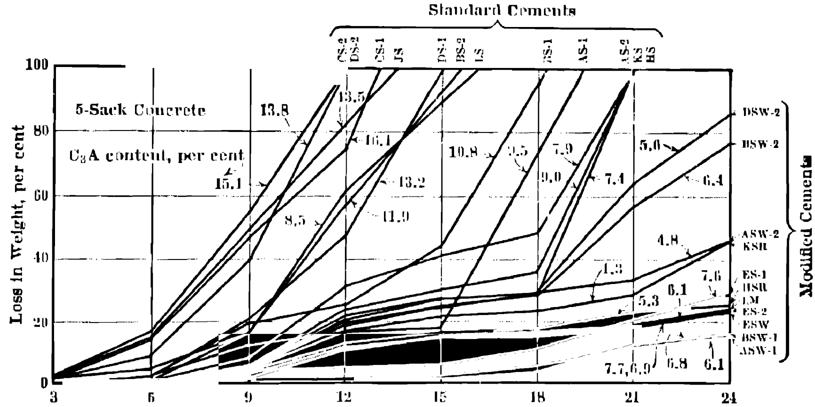

FIG. 26.—Comparison of Performance of Standard Portland Cements with that of Modified Sulphate Resistant Cements. (*Proc. A.C.I.*, Vol. 34, p. 449.)

Animal and vegetable oils, which contain organic acids or which become rancid on exposure, will attack the lime compounds in the cement, form lime soap, and cause surface disintegration. Toch * suggests that this attack is due to the expansion during crystallization of the oleate and stearate of calcium. Therefore in lubricating molds only mineral oil should be used and the amount should be as small as possible.

Seeds † in shells like andaasu, ayry, tucum, and urucury, when subject to moisture, generate uluric acid, which attacks the lime in the cement. Crushed seeds which in moist surroundings generate considerable carbonic acid will also react adversely on lime compounds. Usually the acetic or lactic acids in silage are too weak to attack a dense, well-made mortar but the spillage of milk and cream on creamery floors produces pronounced attack on cement surfaces and mortar joints. Light, refined molasses * may attack concrete containers in time. Tannic acid, commonly found in the top soil overlaying sand and gravel deposits, may cause a marked reduction in the strength of a cement mortar if 0.1 per cent is present in the sand or gravel.

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* J. C. Hain, *Engr. News*, Vol. 53, p. 279, 419.

† F. W. Friese, *Concrete and Const. Engr.*, Vol. 27, p. 347.

Weak solutions of sulphuric or hydrochloric acid (less than 0.3 per cent) will cause a marked attack on cement mortars and concrete. Natural water with *p*H above 7.0 has a negligible attack on cement, but with a lower *p*H value the lime is removed from the cement in proportion to the decrease in the *p*H number; and the strength of the mortar is thereby reduced.† Mine waters are likely to run high in acidity and consequently aggressively attack mortars and concretes.‡

364. Effects of Sugar on Cement.—The addition of as small an amount as one-eighth of one per cent of sugar to cement has been reported to produce a marked delay in the time of set and practically to destroy the early strength.§ Additions of sugar, less than 2 per cent, appear to increase the strength at an age of two or three months. By some, the action of sugar is attributed to the formation of a soluble calcium saccharate ($C_{12}H_{22}O_{11} \cdot CaO + 2H_2O$).

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* M. N. Clair and M. A. Morrissey, *Engr. News Rec.*, Vol. 111, p. 775.

† Bailey Tremper, *Contract Record*, Vol. 45, p. 1441.

‡ A tabulation summarizing the Effect of Oils and Miscellaneous Liquids on Concrete and Method of Protective Treatment Where Required is given in Appendix 17 of the Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete. (See *Proc. A.S.T.M.*, Vol. 24, p. 381.)

§ Parsons, *Engr. News*, 1887, Vol. 2, p. 461; also see series of letters in Vol. 69, pp. 126, 127, 478, 1077.

CHAPTER X

NATURAL AND OTHER HYDRAULIC CEMENTS

NATURAL CEMENT

365. Definition.—Natural cement is made by burning a natural argillaceous limestone at a low red heat which is sufficient to drive off carbonic oxide (CO_2). Additions up to 5 per cent of non-deleterious materials are permitted after burning. The clinker must be finely ground to provide hydraulic properties.

366. Process of Manufacture.—The limestone, containing from 15 to 35 per cent clay, is burnt in vertical kilns 30 to 40 ft. high and 10 to 15 ft. in diameter. The common type of kiln consists of a cylindrical steel shell open at the top and lined with fire-brick. In operating a kiln, thick layers of limestone and thin layers of soft coal are alternately dumped into the top of the furnace and the burnt clinker is drawn off at frequent intervals from the bottom. As the limestone descends in the kiln, water is first driven off from the rock. At a temperature of about 700° C. magnesian carbonate begins to decompose. Lime carbonate dissociates at 900° C. and clay at a somewhat higher temperature. The alumina and iron oxide set free by the decomposition of the clay combine with the lime and magnesia and, if the final temperature be high enough, lime and magnesian silicates will be formed. The process is run continuously and about one-third of the charge, in the form of clinker, is daily withdrawn from the kiln.

On account of the variations in the quality of the raw material and on account of non-uniformity in burning different parts of the charge, a considerable portion of the resultant clinker is either under-burned or over-burned. According to Eckel from 10 to 33 per cent of the resultant product cannot be used. After the clinker has been removed from the kiln it is allowed to season in the air in order that any under-burned clinker may be slacked before grinding. Sometimes slacking is accelerated by steaming the clinker.

The burnt clinker is first passed through a stone crusher and then fed to some form of apparatus for grinding it to the requisite fineness. Formerly, all mills used the millstone grinders commonly employed in flour mills. More recently, however, a decided improvement in the fineness of grinding has been effected by the introduction of ball mills, tube mills and other modern equipment used in grinding Portland cement.

Natural cement is sold by the barrel (4 one-cubic-foot sacks). The weight per barrel is 282 lb. net.

367. Characteristics of Natural Cement.—Natural cement is an impalpable powder varying in color from yellow to brown and in specific gravity from 2.80 to 3.00. It resembles hydraulic lime inasmuch as it is made from a natural argillaceous limestone and will set when mixed with water either in air or under water. On the other hand, natural cement clinker slakes but little, if any, when water is poured upon it.

Most natural cements are not so finely ground as Portland cements although much improvement in this important property has been effected in recent years.

Natural cement requires more water for normal consistency and sets much more rapidly but with a less evolution of heat than Portland cement.

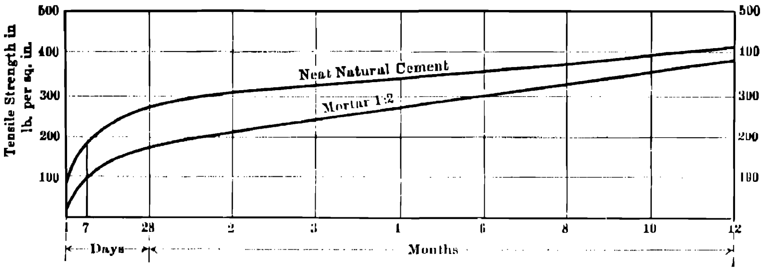

FIG. 1.—Tensile Strength-Age Curves for Neat and 1 : 2 Natural Cement Mortars (From Taylor's *Practical Cement Testing*.)

For pastes of normal consistency the time of initial set will usually vary from fifteen minutes to one hour and final set will generally occur within three hours. An excess of water greatly retards the setting of natural cement pastes. Aeration also retards the set of natural cement.

On account of the variability of the raw materials employed in manufacture, natural cements differ considerably in chemical composition. Even in the same brand considerable differences in the composition are common owing to variations in the rock and degree of calcination. The approximate ranges in amounts of the chief chemical compounds found in natural cements, as obtained from over 100 analyses given in Eckel's *Cements, Limes and Plasters*, Ch. XIX, are as follows: 30 to 60 per cent of lime (CaO); 15 to 35 per cent of silica (SiO_2); 1 to 25 per cent of magnesia (MgO); 2 to 20 per cent of alumina (Al_2O_3); 1 to 19 per cent of iron oxide (Fe_2O_3); and, in general, less than 10 per cent of water (H_2O), carbon dioxide (CO_2), the alkalies (K_2O, Na_2O), and sulphur trioxide (SO_3).

368. Properties of Natural Cement.—Because of variations in composition and manufacture, the properties of natural cements, even those of the same brand, often differ considerably. In Fig. 1 are shown the average tensile strength results of numerous tests made by W. P. Taylor on different brands of natural cement. Attention is called to the regular increase in tensile strength which accompanies an increase in the age of briquettes. Although natural cement gains its full strength much less rapidly than Portland cement, it does not, in general, exhibit marked retrogression in strength, even when tested neat. This fact is well illustrated by Fig. 2 which shows the results of long-time tensile tests on three brands of natural and one brand of Portland cement used on the New Croton Dam. In these tests the mortars were made with crushed quartz passing a No. 20 sieve and retained on a No. 30 sieve. The number of specimens per point on the diagram ranged from 15 to 14,740. Nearly all the tests were made by one operator.

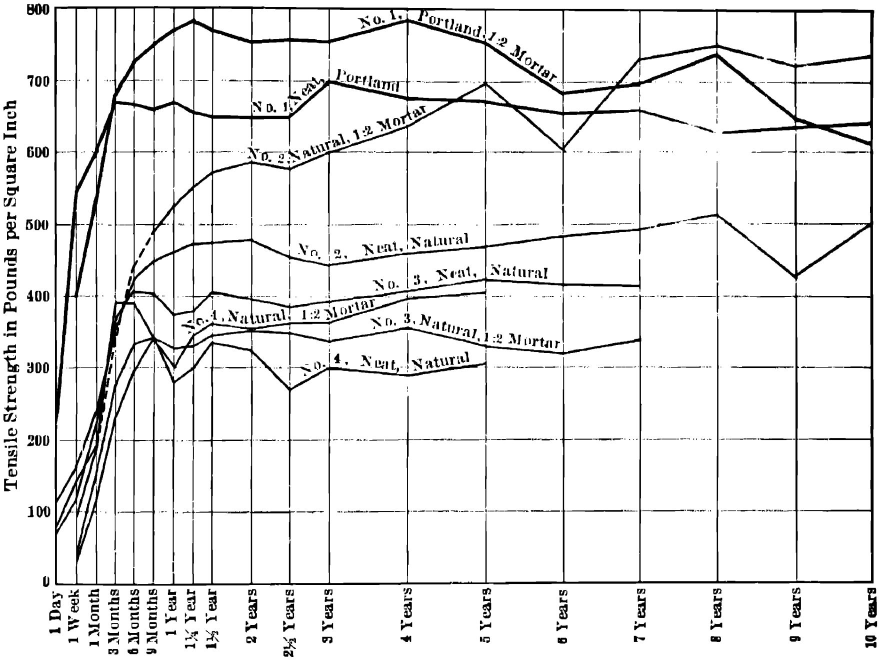

FIG. 2.—The Effects of Age on the Tensile Strengths of Natural and Portland Cements Used in the New Croton Dam. (G. G. Honness, *Trans. A.S.C.E.*, Vol. 76, p. 1038.)

The ratios of tensile strengths of 1 : 2, 1 : 3, and 1 : 4 natural cement mortars to that of neat natural cement when moist-cured 6 mo. Wheeler (*Rept. Chief Engr.*, 1895, p. 2982) found to be 0.65, 0.45, 0.35.

Natural cement in good condition should exhibit minimum tensile strengths in 1 : 3 mortars of standard sand and standard consistency (Art. 417) not less than 75 lb./in.^{2} after 7 days and 150 lb./in.^{2} after 28 days of moist curing. In compression the strength of similar mortars at 7, 28, and 360 days should average 450, 1000, and 2500 lb./in.^{2}, respectively.

Exposure of natural cement to air is likely to cause a reduction in the tensile strength of mortars made from the aerated cement. Regaging neat natural cement mortars with water adversely affects their strengths. Some of Wheeler's tests (*Rept. Chief Engr.*, 1895, p. 2980) indicate that the reduction in tensile strength for a single regaging at the end of one hour was 30 per cent and regaging three times in three hours caused a reduction of 40 per cent. Natural cement mortars are adversely affected by freezing and thawing in about the same proportion as Portland cement mortars, but their final strengths after such action are much lower.

369. Uses and Production.—Until the beginning of the twentieth century natural cement had been extensively used in monolithic constructions in concrete in which great strength was not required. The quicker-hardening and superior strength properties of Portland cement and the lowering of the price of the latter have practically eliminated natural cement from that field. Natural cement now finds use chiefly in masonry mortars for sewers, buildings, and various types of unit masonry constructions. The quantity of natural cement produced annually in the United States approximates two per cent of the production of Portland cement. Its cost is about 20 to 30 per cent less than that of Portland cement.

MISCELLANEOUS CEMENTS

370. White Portland Cement.—Stainless white Portland cements of high strength are used in ornamental work both interior and exterior, in making building blocks, cast stone, stucco, stainless mortar, and in marking highway lanes. In order to obtain the white color it is necessary to use raw materials with a low content of iron oxide. Generally less than one per cent of this oxide is present in the finished cement. Furthermore, it is necessary to use fuel free of pyrite and to burn at a temperature above the normal. Consequently white Portland cement is somewhat more expensive than the ordinary variety. In physical properties, white Portland cements conform to the Standard Specification for Portland Cements, although the strength at one and seven days is sometimes low.*

371. High-early-strength Portland Cements are made from high-limed mixtures, burned twice, and very finely ground. They contain a higher proportion of tricalcium silicate than ordinary Portland cements. Consequently, although setting at about the same rate as ordinary Portlands, they harden much more quickly and with greater evolution of heat. Briquettes of 1 : 3 standard sand mortar should obtain a strength of 275 lb./in.^{2} at one day and 375 lb./in.^{2} at three days.

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* For data on properties, see P. H. Bates, *Trans. Am. Ceramic Soc.*, Vol. 16, p. 551.

Comparing strength of concretes of high-early-strength cements to strength of concrete made of ordinary Portland cements, both having water cement ratios of 0.80, by volume, (see Art. 482) it will be found that in compression the ratio of the former to the latter is approximately 3 : 1 at one day, 2.5 : 1 at 3 days, and 2 : 1 at 7 days. In flexure, the concrete made of high-early-strength Portland cement and $w/c = 0.8$ is approximately twice as strong at ages of 1 to 3 days as that made of ordinary Portland cement. For further data on properties see Art. 356.

Since high-early-strength Portland cements usually cost 40 to 50 per cent more than ordinary Portlands, they are economically used when a high strength is wanted at 1 or 2 days. When 3 days or more curing can be permitted, rich mixes of Portland cement will usually give the required strength at less cost.

Over 4,100,000 bbl. of high-early-strength-cements were produced in this country in 1937. The value at the mill was $1.86 per barrel.

372. Blended Cements.—A blended cement is the impalpable powder obtained by mixing Portland cement with more than one per cent of an admixture, other than a retardant, for the purpose of altering the normal properties of the Portland cement. Mixing is preferably done prior to grinding of the clinker. There are four varieties of admixtures used in making blended cements: (*a*) puzzolanic material; (*b*) inert silicious sands or rocks; (*c*) natural cement or lime; (*d*) accelerators, retarders, plasticizers, and waterproofing materials. Of these the first and second have been used to a considerable extent in marine structures abroad and to some extent for dams and other hydraulic constructions in this country. These two types are high silica cements with low heats of hydration and relatively high resistance to the action of alkali or sea water.

373. Portland-puzzolan cement is made usually by inter-grinding about 30 per cent of puzzolanic material with 70 per cent of Portland cement clinker. Puzzolan is a corruption of the Italian pozzuolana, signifying a volcanic ash. Although not cementitious by itself, a puzzolan carries a type of silicious material which when finely ground will combine with lime in the presence of water and form stable compounds. The more important puzzolanic materials found in nature are volcanic ash and its derivatives, pumicite, tuff, and trass; diatomaceous earths and shales; certain silicious rocks. Among the artificial puzzolans are burned clay, slag, and the very finely divided fly ash from the burning of powdered coal.

The Los Angeles Aqueduct was built of concrete made with cement containing equal parts of Portland cement and tuff. The tuff was consolidated pumiceous rock approximating 70 per cent silica, 12 to 14 per cent alumina, and smaller amounts of iron oxide, lime, magnesia, and alkalies. Since this cement was prepared by grinding the pulverized tuff with the Portland cement to a fineness of 90 per cent passing a No. 200 sieve, the finished product was much finer than normal Portland cements of that period. This cement produced 1 : 2 : 4 concrete somewhat slower in hardening than those made of the Portland cement, but eventually acquired 80 per cent of the strength of similar mixes of Portland. Concrete of this cement was very impervious and showed little shrinkage.

On the Arrowrock, Elephant Butte, and Lahontan Dams, Portland cements interground with equal parts of sand or silicious rock of low puzzolanic activity were used with satisfactory results.

In the recent constructions of the Bonneville Dam and the Golden Gate Bridge Piers, Portland-puzzolan cements were used after exhaustive investigations * by R. E. Davis of the University of California and the U. S. Bureau of Reclamation under J. L. Savage. Of the four common types of Portland cement, Davis tests indicated that a high-lime clinker is the best for making these blended cements. Considering grindability of clinker, strength of concrete, and resistance to sodium sulphate attack, the diatomaceous silicas were the most desirable puzzolans, especially if calcined at 1450° F. prior to blending; but mortars of these cements contract more than those of normal Portlands on drying. The mortars made with cements containing volcanic silicas exhibited less contraction on drying, but were somewhat less strong and resistant to sulphate attack. The mortars made of cements containing silicious rock as puzzolan had low contractions on drying but were considerably lower in strength and sulphate resistance. Also the clinker of these latter cements was harder to grind. In general, the Portland-puzzolan cement concretes exhibited less separation of water after standing in molds and higher impermeability than concretes of the Portland cement. The reduction in heat of hydration of Portland-puzzolan cements is roughly proportional to the percentage of puzzolan. With 30 per cent of puzzolan the heat of hydration is about the same as for low-heat Portlands. Portland-puzzolans made with diatomaceous silicas, volcanic silicas, or limestone are more resistant to sodium sulphate action than the corresponding Portland cements. The plastic deformation of Portland-puzzolan cement mortars under sustained loads is somewhat greater than that of corresponding Portland cement mortars.

Davis' tests on Portland cement blended with fly ash indicate that the latter when containing less than 10 per cent of carbon has excellent puzzolanic properties.

A comparison * of the properties of concretes made with a high-grade

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* See *Jour. Am. Conc. Inst.*, March-April, 1934, p, 369; September-October, 1935, p. 80; May-June, 1937, p. 577; *Special Cements for Mass Concrete*, Bureau of Reclamation.

* From 1938 thesis by G. W. Washa, Ph.D., at Univ. of Wisconsin.

commercial Portland-puzzolan, No. 4, and others made with different types of Portland cement is shown in Fig. 3. Test ages were 28 days.

In England and in Germany blast furnace slag has been used considerably interground with Portland cement to form Portland blast-furnace cement and Eisen Portland cement. The British Portland blast-furnace cement meets the physical test requirements of their standard Portlands but has a lower heat of hydration and high resistance to sulphate attack. The use of these cements in general building construction as well as in marine work appears to be on the increase in those countries.

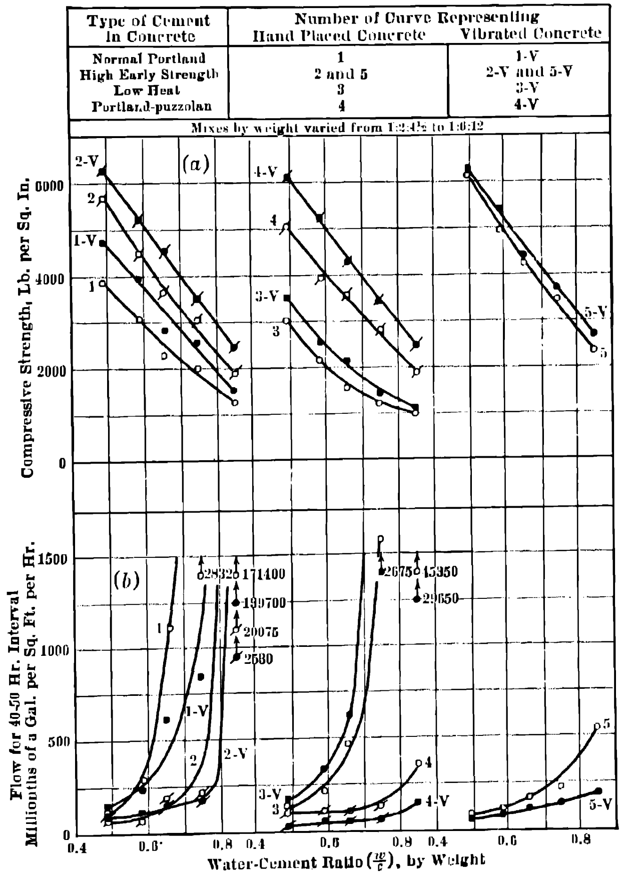

FIG. 3.—The Effects of Different Types of Cement on the Strength and Watertightness of Gravel Concrete Placed by Hand; Also by an Internal Vibrator (Washa).

374. Portland Cement Blended with Natural Cement.—Within the past decade the use of this blend has been revived to some extent. Tests were made at Purdue University on all the more important properties of concrete containing a given brand of normal Portland cement and the same cement blended with 25 per cent of natural cement. In strength and elasticity the concretes of normal cement were slightly superior; but in plastic flow, resistance to fatigue, and in low heat of hydration the blended cement concretes were somewhat better.

In New York State Portland cements blended with 14 to 28 per cent of natural cement have been used in concrete pavements, on account of the superior resistance of concrete so made to the attack of salt used in sanding ice-covered pavements in the winter.*

375. Puzzolan Cements.—Since the beginning of the Christian era the Italians have successfully employed puzzolan cement for various kinds of construction. This cement is made by grinding two to four parts of puzzolana with one part of hydrated lime.† Besides puzzolana, granulated slag, trass, or tuff may be used. When granulated slag is employed, the product is often called slag cement. In 1937 two Alabama plants made from slag and lime all the puzzolan cement produced in the United States.

376. Properties of Slag Cement.—Slag cement may be recognized by its freedom from grit, the extreme fineness to which it is ground, and its lilac color. When a fractured surface of hardened neat paste is exposed to the air, its color gradually turns from a bluish green to white, owing to the oxidation of the sulphides present in the slag. When freshly made, slag cement sets in about the same time as Portland cement but hardens much more slowly. If the slag cement is old, the effect of the caustic soda, which is added to accelerate the set, disappears and the cement becomes very slow-setting. Slag cements require 2 to 4 per cent less water than Portland cement to form pastes of normal consistency. In specific gravity, slag cements vary from 2.7 to 2.9. The proportions of the chemical elements in these puzzolans range about as follows: CaO, 45–55 per cent; SiO_2, 27–30 per cent; Al_2O_3, 10–14 per cent; $Fe_2O_3 < 2$ per cent; $MgO < 4$ per cent; $CaS < 3$ per cent. Most of the American slag cements have a lime ratio between 1.0 and 1.3.

The compressive strengths of rich mixes made from slag cement are less than those of similar Portland cement mixes. In lean proportions, however, the differences in strength are not so great. Mortars of puzzolan cements are tough but have little resistance to attrition. According to the report of the United States Army Engineers ‡ puzzolan cement mortars and concretes should not be used where they will be continually exposed to the air since such exposure produces disintegration by oxidation of th sulphides in the slag. Inasmuch as these cements possess hydraulic properties and are highly silicious, they are commonly believed to be less affected by sea water than Portland cements.*

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* See W. F. Kellerman and D. G. Runner, *Proc. A.S.T.M.*, Vol. 38, Pt. 2, p

† In the setting and hardening of these cements, it is probable that the main35, tions are similar to those discussed in Art. 330 and 373.

‡ *Engr. News*, Vol. 46, p. 180.

377. Masonry cements are used in laying brick, tile, concrete block, stone, or other masonry units. In 1934 Rogers and Blaine, of the United States Bureau of Standards, reported (*Research Paper 746*) on the properties of 41 commercial masonry cements then marketed in the United States. These cements were of the following types: 7 largely Portland; 8 Portland and hydrated lime mixtures; 10 Portland mixed with unidentified plasticizing material—probably limestone dust or silicious material; 2 mixtures of Portland and natural cements; 4 natural cements; 6 containing large amounts of slag; 2 hydrated or hydraulic limes; and 2 not identified. About half these cements contained water-repellent additions of petroleum products or fatty acid derivatives. These water repellents increased water tightness and resistance to freezing but caused more air to be entrapped in the mortars, and thus increased yield. Some conception of the variability and desirability of standardizing these cements may be had from the range observed in the following properties:

Specific weight, 40–90 lb./ft.^{3} (rodded).
Water retentivity of 1 : 3 mortar after 1 min. suction, 53 to 98 per cent.
Shrinkage during first 24 hours, 0.087 to 0.585 per cent.
Compressive strength of 1 : 3 mortar at 28 days, 50 to 3650 lb./in.^{2} (13 cements were below 300 lb./in.^{2} and 22 below 600 lb./in.^{2})
Only 16 of the 41 masonry cements showed high resistance to freezing and thawing by withstanding over 250 cycles, whereas 16 withstood 10, or fewer, cycles.

Such cements should pass the steam pat test for soundness (Art. 419); should not take initial set within 1 hr. and should acquire final set in 48 hr. The compressive strength of three 2-in. cubes of 1 : 3 mortar of standard sand made with a flow of 65 to 80 per cent after twenty-five ½-in. drops in 15 sec. should average 350 lb./in.^{2} or more at 7 days and 600 lb./in.^{2} or more at 28 days. The same type of mortar made with an initial flow of 100 to 115 should have a flow greater than 65 per cent of the initial value after being subject for 1 min. to a suction of 2 in. of mercury. Mortars of such cements should not shrink or expand unduly in hardening, should spread easily under the trowel, should bond well to the masonry, should be durable, and should not effloresce or stain masonry (see A.S.T.M., Des. 91-38T).

378. High alumina cement is an hydraulic cement of recent introduc-[illegible] to the American market, but it has been used commercially in France [illegible]e 1910. It consists essentially of alumina (Al_2O_3) 40.0, lime (CaO)

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* For further results see tests by W. K. Hatt, *Engr. News*, Vol. 45, p. 164.

40.0, iron oxides 15.0, and silica, magnesia, insoluble material, etc., 5.0 per cent. It is manufactured from limestone and bauxite, either by the dry process used in making Portland cement or by fusion in an electric furnace. The American product Lumnite cement is much darker colored than Portland cement.

High alumina cement is more finely ground than Portland, 5 to 8 per cent being held on a 200-mesh sieve. It acquires initial set a bit more slowly and hardens much more rapidly and with a greater evolution of heat than Portland cement. In order to obtain best results it is necessary to flood the work in which Lumnite is used with water, or wet it frequently, after final set has occurred. If the flooding is done too soon or the surrounding atmosphere becomes too dry, a weak, scaly surface forms on the work. Strengths of Lumnite cement mixes wet-cured for 24 hours at room temperature are somewhat higher than the strengths of similar mixes of Portland cement at 28 days. Owing to the high temperatures generated in hardening, Lumnite cement mixes are less sensitive to cold temperatures than Portland cement mixes. Mortars of Lumnite cured in a dry atmosphere contract about as much as similar Portland mixes, but in moist atmosphere they expand more than do Portland mortars.

Owing to the high cost of bauxite, this cement is three to four times as costly as Portland cement. However, on account of its remarkable early strength, a saving in forms and earlier availability of construction attends its use. Another advantage claimed for this cement is its superior resistance to sea water and sulphate-bearing waters.

CHAPTER XI

LIMES AND PLASTERS

LIMES

379. Quicklime.—Pure lime, generally called quicklime, is a white oxide of calcium. Much of the commercial quicklime, however, contains more or less magnesian oxide, which gives the product a brownish or grayish tinge. Quicklime slakes when mixed with water. The specific gravity of pure lime is about 3.40.

Essentially, the process of making lime consists in heating calcite ($CaCO_3$), or magnesian limestone ($xCaCO_3$)$+yMgCO_3$, to a temperature sufficiently high to drive off the carbon dioxide (CO_2). For pure lime carbonate the temperature at which such dissociation takes place is approximately 900° C. Since a considerable length of time is required to calcine limestone at such temperatures, it has been found good practice in operating kilns to use higher temperatures, depending upon the character of the impurities of the stone. However, to avoid burning, which seriously injures the setting properties, high magnesian limes should not be subjected to temperatures above 1000° C. and high-calcium limes should be burnt at temperatures lower than 1300° C.*

Under Serial Designation C 51–28 and C 5–26, the A.S.T.M.† recommends that quicklime be classified as follows:

[1] Size: (*a*) Lump Lime, (*b*) Lump Lime Screened, (*c*) Pulverized Lime.
[2] Chemical composition: (*a*) Calcium Lime, (*b*) Magnesium Lime.

The principal requirements are given in the table on the next page.

380. Burning of Lime.—Limestone is usually burnt in some form of vertical kiln. The raw material is fed in at the top and the finished product drawn off through an opening in the side near the bottom. In general the stacks of these kilns consist of cylindrical steel shells lined with refractory brick. Kilns may be operated continuously or intermittently. To secure the greatest efficiency continuous operation is imperative. The common types of kiln are the mixed-feed and separate-feed kilns. In the mixed-feed type, bituminous coal and limestone are fed into the top of

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* *Trans. American Ceramic Society*, Vol. 13, p. 618, article on burning of limestones by A. V. Bleininger and W. E. Emley.

† See *A.S.T.M. Standards* for the specifications.

CLASSIFICATION OF QUICKLIMES (A.S.T.M.)

Properties Considered.	Calcium Lime.	Magnesium Lime.
Calcium Oxide, min., per cent	75	
Magnesium Oxide, min., per cent	......	20
Calcium and Magnesium Oxides, min., per cent	95	95
Silica, alumina, and oxide of iron, max., per cent	5	5
Carbon Dioxide, max., per cent:		
(*a*) If sample is taken at kiln	3	3
(*b*) If sample is taken any other place	10	10

Lump Lime: Quicklime as it comes from the kilns.

Lump Lime Screened: Lump lime after forking or screening to remove the finer portion.

NOTE.—The portion removed is usually that which will pass a ¼-in. sieve.

Pulverized Lime: Quicklime which will pass a fine sieve of specified size.

NOTE.—The size of the sieve is usually ¼ in.

kiln in alternate layers; in the separate-feed type, the limestone is not brought into contact with the fuel during the burning process. To accomplish this the fuel is burned in a grate which is attached to the sides of the kiln (see Fig. 1), and which is so arranged that the heat produced will ascend into the stack. The majority of the separate-feed kilns burn coal, some wood and a few producer gas. The mixed-feed kiln is more economical of fuel but does not produce as high-grade product as the separate-feed kiln. Most American concerns now use the separate-feed kiln to burn lime. Long rotary kilns similar to those used in burning Portland cement have been installed in some lime-burning plants.

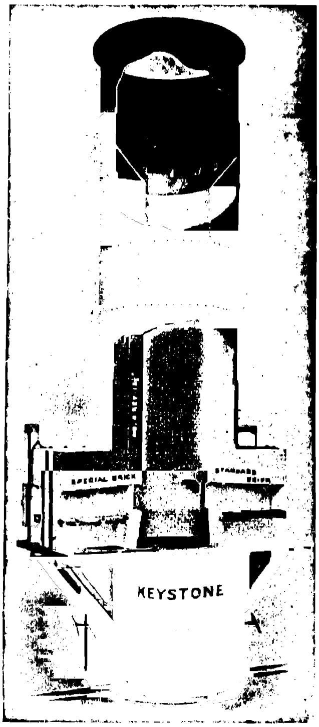

FIG. 1.—A Separate Feed Keystone Lime Kiln.

381. Production Statistics.—Lime is made in nearly all of the United States. Leaders in production are Ohio, Pennsylvania, Missouri, and West Virginia. The total output for the country is about 4,000,000 short tons, with an average value of approximately $7 per ton. About one-third of the lime produced is sold in hydrated form, about one-half is used in chemical and metallurgical operations, one-fourth in building construction, and the remainder is used largely for fertilizer.

382. The Slaking and Hardening of Lime.—The mixing of 56 parts of pure quicklime with 18 parts of water, by weight, causes considerable evolution of heat and an increase of nearly 100 per cent in absolute volume in forming calcium hydroxide, $Ca(OH)_2$. To avoid burning and to promote workable pastes, masons usually slake limes with $1\frac{1}{2}$ to 2 times as much water as lime. Slaking proceeds best at temperatures near the boiling point of water, but care should be taken to avoid overheating as evidenced by the issuance of jets of steam. Limes from coarse-grained stone, lump limes, and pulverized limes usually slake rapidly; limes from fine-grained stones, and dense lumpy limes usually slake slowly. Overburning or underburning of the limestone causes the lime to slake more slowly and injures the mortar strength. With rapid-slaking limes (showing decrepitation and marked evolution of heat within 5 minutes) it is best in slaking to add the lime to the water and keep the lime covered with water, thus avoiding overheating. With slower-slaking limes the water should be added to the lime in amounts sufficient to promote a vigorous reaction without the formation of steam jets. In order to avoid popping of plaster and undue expansion in masonry mortars subjected to moisture, the lime and most of the magnesia should be hydrated. Since the latter hydrates at ordinary temperatures much more slowly than the former, dolomitic and high magnesian limes will require a longer time to hydrate than the high-calcium limes. By maintaining the temperature of the batch at 180° F. either can be hydrated in a couple of days. If the batch is allowed to cool down to room temperature in 6 or 8 hours, then it may require a week or two to hydrate 80 per cent of the magnesia in a dolomitic lime.

In construction, both the shrinkage and the cost of lime mortars are much reduced by adding 4 or 5 volumes of sand to 1 volume of lime putty.

In the hydrating of lime, part of the calcium hydroxide crystallizes and part forms colloids. These components secure a certain amount of rigidity through evaporation and absorption of the surplus water by the surrounding masonry. Final hardening is attained, however, through desiccation of the water and replacement by carbon dioxide from the air. Thus the paste is slowly converted into a carbonate of approximately the same composition as the original limestone. Owing to the inaccessibility of the interior of a masonry joint, this hardening action progresses very slowly and, if the wall is thick, may take years for its completion.

When stored in air, quicklime soon decrepitates because of the absorption of moisture and carbon dioxide and is in time reduced to lime carbonate. Therefore, in order to preserve its hardening power, quicklime must be stored in tight containers. Since ground lime keeps better than lump lime, ground lime can be shipped in open cars, although ground lime for construction is commonly shipped in paper sacks of 67-lb. capacity.

There are two methods of marketing lime designed to overcome the imperfections of job slaking. In a number of metropolitan areas, plants with specially equipped slakers, tanks, and trucks can supply properly hydrated putty in desired quantities. Hydrated lime in powder form is also available.

383. Hydrated Lime.—When quicklime is finely crushed, slaked with a minimum amount of water, and screened or ground to form a fine homogeneous powder, the product is called hydrated lime. If the lime from which it is made is pure, hydrated lime is a white powder having a specific gravity of 2.08; the specific gravity of some dolomitic hydrates may reach 2.40. The magnesia of dolomitic hydrates may not be hydrated owing to insufficient time and temperature used in hydrating. Unless presoaked, mortars made of the hydrates are less plastic than those made of the putties. Hydrated lime is sold in paper bags of 50-lb. capacity or in 100-lb. burlap or cloth sacks. In such containers it may be stored for a much longer time than lump lime without serious deterioration.

384. Testing of Limes.—The A.S.T.M. tentative specifications for structural lime specify certain tests in addition to chemical analysis. A fineness test on lime is recommended to determine the percentage of inert material in the product. For this test a representative 5-lb. sample of lime broken to pass a ¼-in. sieve, is carefully slaked with sufficient water to form the maximum amount of lime putty, care being taken to avoid drowning or burning. After standing for twenty-four hours the paste is washed through a 20-mesh sieve. The stream of water should flow under moderate pressure and rubbing of the material through the screen should be avoided. Not more than 15 per cent of a ground lime or slaked lime should remain on the sieve.

Less than 15 per cent of a commercial hydrate of lime should be retained on a 200 sieve after 30 min. washing of a 100-gram sample with water. Methods are also specified for soundness tests and for estimating the consistency of mortars in the A.S.T.M. Standards. The autoclave test provides a simple method for determining the completeness of hydration.

Tensile strength tests of lime mortar briquets are also sometimes made. When compression or transverse tests are made it is necessary to specify a certain size of test-piece, since the rate of carbonation is affected by the thickness of the specimen. Large cubes have lesser strengths than small ones.

The yield or volume of lime paste which can be made from a given weight of lime is an important factor in estimating the quantity of lime required to make a given amount of mortar. The test can be made in the same manner as indicated in Art. 451, Ch. XII.

385. Properties of Lime.—From a long series of experiments on the strength of lime-mortars made at Iowa State College the results shown in Table 1 have been derived. For some unknown reason the strength of these mortars was somewhat greater at nine months than at one year, although the carbonation process was still incomplete at the end of a year. In general the greater strengths were obtained with the lower percentages of water and sand. The hardening of the calcium limes was more uniform and rapid than that of the magnesian limes, but the latter exhibited higher strengths.*

TABLE 1.—RESULTS OF TENSILE TESTS OF LIME-MORTAR BRIQUETTES MADE AT IOWA STATE COLLEGE IN 1907

Proportions, Lime : Sand.*	% Water.†	AVERAGE STRENGTH OF 10 BRIQUETTES IN LB./IN.²									
		Age 3 Months.					Age 6 Months.				
		Calcium Limes.		Magnesian Limes.			Calcium Limes.		Magnesian Limes.		
		Mason City.	Springfield.	Eagle Point.	Mason City.	Maquoketa.	Mason City.‡	Springfield.	Eagle Point.	Mason City.	Maquoketa.
1 : 1	100	65	96	111	78	128	63	109	154	159	184
1 : 2		76	94	100	92	130	68	97	113	137	167
1 : 3		55	68	90	86	130	53	73	94	119	154
1 : 1	200	45	61	98	54	105	47	62	113	75	153
1 : 2		51	55	90	81	105	53	57	88	98	125
1 : 3		50	55	101	81	100	54	48	104	91	108
1 : 1	300	43	41	120	75	101	42	45	140	96	123
1 : 2		41	45	112	77	86	41	45	114	91	113
1 : 3		46	53	87	70	82	48	51	99	88	96

* A river sand passing a No. 20 and held on a No. 30 sieve was used in all tests.
† Calculated in terms of the weight of the dry hydrate.
‡ Age = 16 weeks.

ANALYSES OF LIMES

Locality.	CaO	MgO	$Al_2O_3+Fe_2O_3$	Loss on Ignition.	Insol. Res.	CO_2
Mason City, Ia.	95.40	0.43	2.98	0.00	1.02	
Springfield, Mo.	94.70	0.40	1.80	2.08	1.00	trace
Eagle Point, Ia.	58.19	33.48	6.60	slight	2.01	
Mason City, Ia.	72.40	15.23	6.03	3.36	2.32	0.10
Maquoketa, Ia.	60.60	35.70	2.10	2.30	0.63	

Compressive tests by W. E. Emley and S. E. Young, of the Bureau of Standards Laboratory, show that the size of the sand grains has a pronounced effect upon the strength of lime mortar.† The tests were made upon 2-in. cubes of 1 part quicklime to 3½ parts sand, by weight. The age at breaking was ninety days. The results of these tests appear in Table 2*b*. It should be noted that the mortars of fine sand gave the highest strength, a condition which does not hold true in mortars made of hydraulic cements. Probably the loss in strength due to the lack of density in the fine-sand pastes is offset by the complete carbonation which is obtained on account of their porous structure.

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* For further data see *Bulletin* No. 1, Vol. 4, Engineering Experiment Station, Iowa State College, Ames, Iowa; *Report of Chief Engineers*, U. S. A., 1896, Pt. 5, p. 2839; *Bulletin* No. 4, Ohio Geol. Survey; *Proc. A.S.T.M.*, Vol. 10, p. 328–40; also Vol. 14, p. 339.

† Reported in *Proc. A.S.T.M.*, Vol. 14, p. 346.

The effect of the proportion of sand on the compressive strength of lime pastes is also shown in Table 2.

TABLE 2.—THE VARIATION IN THE COMPRESSIVE STRENGTH OF LIME WITH (*a*) AMOUNT OF SAND AND (*b*) SIZE OF SAND GRAINS

(Tests by Emley and Young)

Each result is averaged from 3 tests.

(*a*) AMOUNT OF SAND.			(*b*) SIZE OF GRAINS.		
Sand Parts.	Compressive Strength Lb. per Sq.in.		Size of Sand Grains between Meshes No.	Compressive Strength Lb. per Sq. in.	
	High Calcium	Dolomitic.		High Calcium.	Dolomitic
½	273	372	10–20	98	166
1	151	267	20–30	118	214
2	116	217	30–40	138	312
3	112	202	40–60	186	335
4	116	203	60–80	260	444

High-calcium limes expand more in slaking and shrink more in setting than the magnesian limes. They are also more liable to injury through "burning" in slaking. When completely hydrated the dolomitic limes produce stronger mortars and work as smoothly under the trowel.

386. The Uses of Lime.—In construction, slaked lime is chiefly used to make mortar for laying brick and stone masonry and for plastering walls of buildings. When so used, quicklime should be completely hydrated by slaking from 3 to 14 days, depending upon the kind of lime, temperature, and slaking conditions. Hydrated lime, although immediately usable, is usually improved by soaking overnight or longer. Hydrated limes are often added to Portland cement mortars in proportions varying from 5 to 85 per cent of the weight of the cement. This is done to increase plasticity and workability. In order to avoid excessive expansion, it is not advisable to incorporate more than 10 per cent of dolomitic hydrate in such mortars if they are to be subjected to moist conditions, unless the magnesia in the lime is known to be hydrated, or has been hydrated by presoaking for two or three weeks. Hydrated lime is used also in making the popular stucco finish for exterior walls * and to increase the imperviousness of Portland cement concrete (see Art. 533).

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* See specifications for Portland Cement Stucco, *Proc. N.A.C.U.*, Vol. 7, p. 586.

✓ **387. Hydraulic Lime.**—In the middle of the eighteenth century John Smeaton, the celebrated English engineer, was confronted with the problem of finding a cement which could be used in the construction of the famous Eddystone Lighthouse. The only cementing material then in use was quicklime, which does not harden under water. After a series of experiments he discovered that an impure limestone containing a small amount of clay, if calcined in the ordinary way, would produce a lime which would slake upon the addition of water and would harden under water. On account of the latter property the name hydraulic lime was given to this material. In France and southern Europe it is still used to a considerable extent. On account of the prevalence of raw materials suitable for the manufacture of Portland and natural cements no hydraulic lime is manufactured in the United States. However, Lafarge cement, a by-product in the manufacture of hydraulic lime, is used considerably in this country.

Hydraulic lime is manufactured in the same way as quicklime, although a somewhat higher temperature is required in burning. In slaking, considerable care is required to provide just sufficient water and no excess, since an excess would cause the lime to harden. After slaking, the coarse material is screened out and the fine product bagged for market. The coarse particles are finely ground and sold for Grappier cement. The specific gravity of hydraulic lime is about the same as that of the natural cement. Mortars made from the famous limes of Tiel, France, also have about the same strength as those made from natural cement.

388. Lafarge Cement.—This cement is used in America for stucco work and in laying marble and other masonry which is stained by natural or Portland cement mortars. It is a Grappier cement made as indicated above. Published analyses show it consists principally of lime (58 59 per cent) and silica (27 31 per cent) with 2.6 to 4.5 per cent of alumina and smaller percentages of iron oxide, magnesia and the alkalies. According to the manufacturers' circular * this cement has a specific gravity of 2.6, an initial set in 4 hours, final set in 10 hours, and a residue on 100-mesh sieve of 0.6 per cent. Its strength neat and in a 1 : 2 mortar is about 60 per cent of that demanded of a standard Portland cement at 7 and 28 days. At two years the record gives a neat strength of 665 lb. per square inch.

GYPSUM PLASTERS

389. Introduction.—On account of the wide use of gypsum plasters in the arts and in building construction a brief résumé of some important facts concerning them will be given. In the United States plaster of Paris, stucco, wall plaster, and hard finish plaster are extensively used in wall construction. In Germany flooring-plaster, made by calcining gypsum at a high temperature, has been considerably used. In all of these powders, gypsum in a more or less dehydrated state is the essential element. When water is added to these substances they become rehydrated forming compounds similar to those existing before calcination.

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* Eckel's *Cements, Limes and Plasters*, p. 189.

390. Gypsum.—There are two commercial varieties of crude gypsum, rock gypsum and gypsum earth or gypsite. These substances consist principally of a hydrous sulphate of lime ($CaSO_4+2H_2O$), with varying percentages of silica, carbonate of lime, carbonate of magnesia, and iron oxide. Pure gypsum is a white translucent crystalline mineral, so soft that it can be scratched with the finger-nail. When heated to 400° F., pure gypsum loses its luster and its specific gravity is increased from 2.3 to approximately 2.95 due to the loss of water of crystallization.

Deposits of gypsum are numerous and widely scattered. The rock deposits occur in beds commonly traversed by thin strata of limestone and often adjacent to rock-salt deposits. Gypsite formations consist of masses of gypsum crystals interspersed with clay and sand. The states leading in the production of gypsum are New York, Iowa, Michigan, Texas, California, Nevada, and Oklahoma. Among the countries of the world the United States ranks first and produces about two-fifths of the total supply. The value of the 3,058,166 short tons of crude gypsum produced in the United States in 1937 was $4,782,503. Of the quantity obtained in this country, about two-thirds is calcined and made into plasters; approximately one-fourth is sold in crude state to Portland cement manufacturers.

391. Manufacture of Plasters.—For making the refined grades of plaster of Paris in which a uniform degree of calcination is required the oven process is much used in Europe. In this country, however, on account of expense and time required, this method has been discarded in favor of the kettle and rotary process, the former being used in nearly all plants making plaster of Paris or cement plaster. Hard finish plasters are made in kilns similar to the mixed-feed kilns used in calcining lime.

After the raw material has been excavated or mined it is put through one or more crushers, and if the kettle process is used, is then ground by buhr-stones or like mills until about 60 per cent will pass a No. 100 sieve. In the rotary process the final pulverization is omitted until calcination is completed.

The kettles employed for calcination are 8 or 10 feet in diameter and about 6 or 7 feet high. The sides are made of sheet steel and the bottoms of cast iron. Each kettle is placed with its top just above the working floor. The lower portion of the kettle is enclosed in a masonry chamber which serves to support the kettle and distribute the heat from the grate fire about it. Two or four horizontal flues running through the kettle increase the circulation of heat. A power-driven stirrer is used to agitate the contents of the kettle and thus prevent the bottoms from burning out. The hot gases and steam are led away through a stack.

After the pulverized material has been chuted into a kettle, heat is very slowly applied until the mechanically held water is driven off. At a temperature just above the boiling-point of water the whole mass bubbles up violently and then sinks. At 290° F. the combined water begins to boil out and between 340° and 396° F. the process is stopped. The impure gypsites generally require a higher temperature than the purer rock gypsums. In many plants the final temperature is judged by the appearance of the boil, although thermometers are often used in making plaster of Paris.

By the kettle process, it requires about two or three hours to calcine a charge yielding 5 or 6 tons. The calcined product is then run from the bottom of the kettle into a cooling vat, whence, after partially cooling, it is sent to the screens. Residues from the screens are reground; the fines are stored in large bins.

In the rotary process the raw material is crushed to pass a 1-in. mesh and is then fed into the upper end of a cylinder which rotates about an axis slightly inclined to the horizontal. Calcination is accomplished by the introduction of hot furnace gas, the temperature of which can be regulated by an admixture of a forced draught of air. When properly roasted the material is conveyed to brick-lined calcining vats in which further changes are brought about by the heat within the material. The product from the vats is then finely ground and screened. Continuous operation is the main advantage which this process possesses over the kettle process.

In order that the workman may properly handle plaster of Paris or stucco, it is necessary to delay the time of setting. This is accomplished by adding a fraction of one per cent of a retardant like glue, sawdust or blood after the plaster has cooled.

To increase the cohesiveness of wall plaster, cattle hair or wood fiber is introduced. For this purpose about 2 or 3 lb. of finely picked hair or 60 to 100 lb. of finely pulverized wood fiber is added to each ton of plaster.

Wall plasters made from pure raw materials are generally adulterated with 15 to 20 per cent of hydrated lime to increase the plasticity of the product. The term "stucco" is sometimes applied to a plaster so treated. Wall plasters made from raw materials containing considerable clay do not require such addition.

Many of the plasters are packed in jute sacks holding 100 lb. each. Recently a considerable effort has been made to further the use of paper sacks, thus obviating the traffic in empty jute bags, which is a considerable nuisance and expense.

✓ **392. Plaster of Paris.**—Plaster of Paris is produced by incompletely dehydrating pure, finely ground gypsum at a temperature somewhat less than 370° F. Most plasters closely approach the theoretical composition —$CaSO_4+\frac{1}{2}H_2O$—which contains about 6.2 per cent of water. Plaster of Paris is a white powder having a specific gravity of 2.57. When tempered with sufficient water to form a plastic paste it sets in 5 to 10 min.

The setting of plaster of Paris is attributed to the formation of gypsum crystals from a supersaturated aqueous solution. Why the rapidity of setting is so very much greater when the powder consists of plaster of Paris than when it consists of anhydrous gypsum plus water is a point not yet settled. When substances of a colloidal nature (glue for example) are mixed with the plaster the formation of crystals is hindered and the time of set retarded.

In hardening, plaster of Paris first shrinks and then expands. The latter property makes the material valuable in making casts, since a sharp impression of the mold can be secured. Owing to the rapidity of set and difficulty in working, its use in structures is limited to ornamental work.

393. Gypsum Wall Plasters are divided into four classes [*] as follows: *Gypsum neat plaster* consists of 60.5 per cent or more calcined gypsum, the remainder being material added at the mill for controlling workability, time of set, and cohesiveness. Calcined gypsum signifies commercial plaster of Paris, $CaSO_4+\frac{1}{2}H_2O$. *Gypsum wood-fibered plaster* carries 60.5 per cent or more by weight of calcined gypsum, 1 per cent or more of wood fiber to increase the cohesiveness, and other materials to control workability and time of set. *Calcined gypsum* for finishing coat, which may or may not carry a retardant, is divided into two grades, "white" and "gray." *Gypsum ready-sanded plaster* consists of a cementing material, predominantly calcined gypsum, which has been mixed at the mill with the proper proportions of sand and other desirable constituents. It is prepared for use simply by adding water. The two grades of gypsum ready-sanded plaster are scratch, or first coat, and the browning, or second coat. Scratch coat ready-sanded plaster contains not over two parts sand by weight to one part of cementing material. The cementing material carries at least 60.5 per cent by weight of calcined gypsum plus other ingredients for controlling workability, time of set, and cohesiveness. Second coat ready-sanded plaster contains not over three parts sand with the same type of cementing material as in first coat ready-sanded plaster.

Specifications of the American Society for Testing Materials require that gypsum neat plaster mixed with 3 parts of standard sand shall set in 2 to 32 hours and, when mixed with 2 parts of standard sand, shall have a tensile strength of not less than 75 lb./in.^{2} at an age of 7 days. Gypsum wood-fibered plaster shall set in not less than $1\frac{1}{2}$ hours nor more than 8 hours, and shall develop a tensile strength of 125 lb./in.^{2} in seven days.

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[*] This classification is based on *A.S.T.M. Standards*, Des. C28–30.

Not less than 60 per cent of the calcined gypsum for finishing coat shall pass a 100-mesh sieve; when not retarded it shall set in from 20 to 40 minutes (when retarded, from 40 minutes to 6 hours); and shall have a tensile strength of 200 lb./in.^{2} at seven days. Scratch, or first coat, ready-sanded plaster shall set in from 1½ to 7 hours, and shall have a tensile strength of 75 lb./in.^{2}, while browning, or second coat, ready-sanded plaster shall set in from 2 to 6 hours, and shall have a tensile strength of 50 lb./in.^{2} at 7 days.

A large number of tests (*Rept. Iowa Geol. Surv.*, Vol. 12, p. 232) indicate that gypsum plasters gain one-half of their one-month strength in a day, and gain but little strength after one month. Plaster and sand mortars of 1 : 1 proportions may be expected to develop 80 per cent of the neat strength at corresponding ages, while those of 1 : 2 proportions generally possess one-half to two-thirds of the neat strength. Compressive strength of plasters one week old and air cured vary from 887 to 2236 lb./in.^{2} These tests also show that the adhesion of plaster mortars to a fractured surface of plaster is approximately two-thirds of the strength of the mortar.

Gypsum wall plasters have become quite popular in recent years because they are ready for use when brought to the job and also because they harden more rapidly than do the older lime plasters. However, lime plasters are more plastic and may, therefore, be loaded with 3 or 4 parts of sand, whereas the gypsum plasters can carry only 2 or 3 parts; also, when properly slaked, lime plasters form eventually just as satisfactory walls as those made from cement plasters.

394. Hard-finish Plasters.—By burning gypsum to a considerably higher temperature than the calcining temperature of cement plaster, treating with certain solutions like alum and Glauber's salts, there may be produced plasters which set slowly but ultimately become very hard. Such plasters may be polished to form a smooth surface and make a very satisfactory finish for interior walls. Often walls of these plasters are marked to imitate tiling with pleasing results.

Keene's cement is made by burning a very pure rock gypsum at a red heat (1300° F.), cooling, and then adding less than one per cent of potassium and aluminum sulphates to accelerate the set. Subsequently the material is ground so that 90 per cent or more will pass a No. 100 sieve. Keene's cement is thus nearly pure calcium sulphate ($CaSO_4$) of pure white color. It is not injured by storage, and mortars of it may be retempered. Set occurs between 1 and 4 hr. At 7 days the neat tensile strength will usually exceed 450 lb./in.^{2}.

Mack's cement is made by burning gypsum at a very high temperature and adding about 0.4 per cent of burnt Glauber's salts (Na_2SO_4) or potassium sulphate. (K_2SO_4). It is said to form an unusually hard, dense and durable surface which will take paint well.

395. Other Gypsum Building Materials.—Blocks and tile made from wall plaster and suitable for floor and interior wall construction are now on the market. These forms are light, can be easily sawn to desired shape, possess sufficient strength for many types of construction and have a high resistance to fire.* Mixed with fine cinders or wood chips and sufficient water to form a thin consistency, wall plaster has been used in making floors for buildings. Such floors can be much more rapidly constructed than concrete floors, owing to the rapidity with which the plaster hardens.† However. they are neither so resistant to fire nor so strong as concrete floors.

Another product of recent origin is plaster board. It is made of thin layers of cardboard or wood cemented together by wall plaster. Thin sheets of this material are used in place of lath; sheets $\frac{3}{8}$ in. thick, 3 to 4 ft. wide, and 6 to 10 ft. long are used in place of lath and plaster.

Pyrocell is a finely ground gypsum powder containing an admixture which, on being mixed with water, forms a gas and expands the mixture to 3 or 4 times its volume. This inflated paste hardens into a light, cellular, fire-resistant mass possessing good acoustical and insulating properties.

To cap concrete, brick, and other masonry materials for compression tests, gaging plaster, Hydrocal, and Hydrostone may be used. In a consistency of thick cream they attain the following strengths in 2-in. cubes after 2 hours in air: gaging plaster, 1400 lb./in.^{2}; Hydrocal, a casting plaster, 3500 lb./in.^{2}; and Hydrostone, a special type of Hydrocal, 4500 lb./in.^{2}.

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* See *Gypsum as a Fireproofing Material*, by V. G. Marani, *Jour. Cleveland Engr. Soc.*, Vol. 7, p. 213.

† See *Bulletin* No. 25. Public Works of the Navy, January, 1917.

CHAPTER XII

METHODS OF TESTING HYDRAULIC CEMENTS

396. Necessity for Testing Cement.—Experience has shown that it is practically impossible to make large quantities of cement without any variation in quality. To be sure, some mills working with raw materials which run very uniformly and using the best of equipment and methods of operation will have very few unsuccessful " burns " in a year, while others will be less fortunate. Nevertheless the consumer has little chance of ascertaining how his particular carload of cement was made; therefore, if he has under way a construction of any importance, he ought to satisfy himself regarding the quality of his purchase. He should test his cement not only to see that he gets what he has paid for but also to forestall the possibility of a failure through the use of defective material.

In engineering construction the main qualifications demanded of a cement are permanency of structure, strength, and a rate of setting suitable to the demands of the work. To determine these qualifications, both physical and chemical tests are made, the former, on account of importance, more often than the latter.

As a result of long experience the physical tests which have come into general use in determining the acceptability of cement are: (1) soundness or constancy of volume, (2) strength, (3) time of set or activity, and (4) fineness. In order that the results of such tests made by different parties may accord as nearly as possible, it is necessary that a standard method be rigidly adhered to and that only experienced operators, who fully appreciate the necessity of eliminating personal equation from all manipulations, be employed.

In the fine type of the following sections will be considered the Standard Methods of Sampling and Testing Portland Cement of the American Society for Testing Materials. For standard specifications, see A.S.T.M. *Standards*. The methods of testing are adapted to any of the hydraulic cements with the exception of the accelerated soundness test which is used with Portland cements only. The sections of the standard methods will be numbered consecutively but will be interspersed with comments and references to other methods of testing which will appear in large type. Since it is only by close observance of standard methods that uniformity in testing may obtain, any divergence by the operator should be stated with full explanation in reporting the results of tests.

STANDARD METHODS OF SAMPLING AND TESTING PORTLAND CEMENT *

A.S.T.M. DESIGNATION: C 77–37

These methods are issued under the fixed designation C 77; the final number indicates the year of original adoption as standard or, in the case of revision, the year of last revision.

ADOPTED, 1904; ISSUED IN AMENDED FORM UNDER PRESENT DESIGNATION, 1930; REVISED, 1932, 1937.

SAMPLING

397. A.S.T.M. Method.—

Size and Number of Samples.—1. Samples for purpose of tests shall weigh at least 4 lb.

2. Test samples shall be either individual or composite samples, as may be ordered, and one test sample shall represent not more than 300 bbl., unless otherwise specified by the purchaser.

Methods of Sampling.—3. When cement is sampled in cars, trucks, boats, warehouses, etc., one sample shall be taken from one sack in each 40 sacks (one sample per 10 bbl.), and combined to form one test sample. In the case of truck samples where the cement is being trucked from one mill, it is permissible to combine the samples from several trucks to form a test sample representing not more than 300 bbl. When sampling bulk shipments, representative samples shall be taken from well distributed points.

4. The cement may be sampled at bulk storage points by any of the following methods:

(*a*) *From the Conveyor Delivering to Storage.*—At least 4 lb. of cement shall be taken from at least each 300 bbl. passing over the conveyor. This may be secured by taking the entire test sample at a single operation, known as the " Grab Method," or by combining several portions taken at regular intervals, known as the " Composite Method." When obtaining a composite sample this shall be secured by combining approximately equal weights taken at regular intervals, each portion representing approximately 10 bbl. Automatic samplers may be used in obtaining samples.

(*b*) *From Storage by Means of Proper Sampling Tubes.*—Tubes inserted vertically may be used for sampling cement to a maximum depth of 10 ft. Tubes inserted horizontally may be used where the construction of the storage permits. Samples shall be taken at points well distributed over the storage.

(*c*) *From Storage at Points of Discharge.*—Sufficient cement shall be drawn from the discharge openings to obtain samples representative of the cement, as determined by the appearance at the discharge openings of indicators placed on the surface of the cement directly above these openings before the drawing of the cement is started. One 4-lb. sample shall be taken for at least each 300 bbl.

Preparation of Sample.—5. The sampling shall be done by or under the direction of a responsible representative of the purchaser.

6. Samples shall be shipped and stored in moisture-proof, air-tight containers.

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* Now published in 16 separate Tentatives and Standards. Basic procedures are substantially as here stated, except as noted.

Before testing, samples shall be thoroughly mixed and then passed through a No. 20 sieve in order to break up lumps and remove foreign materials.

398. Comments on Sampling.—Bearing in mind the importance of obtaining a fair and representative sample of the cement, it is well to exercise much care in the selection, storage, and mixing of it. If the cement is stored in bags in a car or warehouse the selection of the bags to be sampled should be made in such manner that the entire lot will be represented. It is not sufficient to select bags from the outside of a pile, but those within should also be sampled.

In all cases a sufficient quantity should be collected so that the contemplated series of tests may be duplicated without resampling. Although it is not always possible to obtain a second sample; yet, it is worth while in sampling bags or barrels, to number the bag and sample alike. The sample may be taken conveniently by the auger shown in Fig. 1 or by a long-handled spoon.

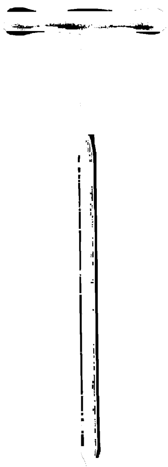

Fig. 1.—Cement Sampler.

Storage of the Sample.—Because it is important that the properties of the cement shall not be influenced by changes in the humidity and temperature of the air, standard storage conditions should be maintained. If paper or cloth sacks are used in collecting samples, they should be enclosed in a tight waterproof container for shipment to the laboratory. In the laboratory, clean cans fitted with tightly fitting covers will be found convenient receptacles for samples which must be stored for several weeks. The storage room should be dry and its temperature maintained at approximately 70° F.

Mixing Samples.—If information concerning the uniformity of a quantity of cement is desired, the individual samples should be tested separately. If a fair number of samples are taken from a car load, say ten to twenty, such procedure would be very costly if all the tests were made on each sample. In order to cut down the expense of testing and at the same time secure information regarding the uniformity of the material, the accelerated soundness may be run on every sample and the remaining tests made on a composite sample consisting of equal portions taken from each individual sample. Before making any tests, each individual or composite sample should be placed on a smooth dense surface and turned over 30 or 40 times with a trowel.

Quartering.—The portions of a sample required for the various tests may be fairly obtained by spreading the cement into a flat cylindrical pile and removing sector slices sufficient in quantity for each test. Such proceeding is sometimes called "The method of quartering." Sample splitters are also manufactured for such purposes.

CHEMICAL DETERMINATIONS

399. Purposes.—Chemical analyses are regularly made by the manufacturer to whom they afford very valuable indications concerning the proportioning and burning of the cement. Sometimes analyses are made by consumers who wish to determine whether the cement has been adulterated or has excessive amounts of injurious substances such as magnesia and sulphur trioxide. As a rule the results of an analysis are of much less value to the consumer than the physical test indications. Only the methods for the more important determinations appear in the following articles; for more complete instructions see A.S.T.M., Des. C114–46.

400. A.S.T.M. Methods for Number of Determinations and Procedure.—

7. (*a*) When cement is sampled in accordance with Section 3 at least one determination of loss on ignition, insoluble residue content, and magnesia content shall be made for each 10 test samples taken, and at least one determination of sulphuric anhydride (SO_3) content shall be made for each 3 test samples. In case of truck deliveries and car deliveries the sulphuric anhydride (SO_3) content shall be determined on each test sample. When the total number of test samples taken is less than either of the groups above specified at least one determination shall be made for each chemical requirement.

(*b*) When cement is sampled in accordance with Section 4, at least one determination of loss on ignition, insoluble residue content and magnesia content shall be made for each 15 test samples and at least one determination of sulphuric anhydride (SO_3) content shall be made for each 3 test samples; provided that at least one determination for each chemical requirement shall be made on each bin sampled.

(*c*) The chemical determinations may be made either on composites of the original test samples or may be made on individual test samples selected at random at the option of the purchaser.

(*d*) The chemical determinations shall be made in accordance with the procedure described in the following Sections 8 to 17 (Note).

NOTE.—This method of chemical analysis is not considered as possessing the highest obtainable accuracy, but is an acceptance method to be followed in making acceptance tests on cements covered by specifications requiring that tests be made in accordance with the analytical procedure contained in this standard.

401. A.S.T.M. Method for Finding Loss on Ignition.—

8. Heat a 1-g. sample of cement in a weighed covered platinum crucible of 20 to 25-ml. capacity, as follows, using either Method 1 or 2 as specified.

(*a*) *Method 1.*—Place the crucible in a hole in an asbestos board, clamped horizontally, so that about three fifths of the crucible projects below the board, and heat at a full red heat (900 to 1000° C.) for 15 min.; check the loss in weight by a second heating for 5 min. Take care to wipe off particles of asbestos that may adhere to the crucible when withdrawn from the hole in the board. Greater neatness and shortening of the time of heating may be secured by making a hole to fit the crucible in a circular disk of sheet platinum and placing this disk over a somewhat larger hole in an asbestos board.

(*b*) *Method 2.*—Place the crucible in a muffle furnace at any temperature between 900 and 1000° C. for 15 min. and check the loss in weight by a second heating for 5 min.

402. A.S.T.M. Method for Determining Insoluble Residue.—

9. Add 25 ml. of cold water and 5 ml. of HCl (sp. gr. 1.19) to a 1-g. sample of cement. Heat the solution and grind the material with the flattened end of a glass rod until it is evident that decomposition of the cement is complete. Dilute the solution to 50 ml. and digest on a steam bath for 15 min. Filter the residue, wash six times with hot water, and digest the filter paper and contents in about 30 ml. of a sodium carbonate solution (5 per cent), the liquid being held at a temperature just short of boiling for 15 min. Filter the remaining residue, wash twice with hot water, then with a few drops of hot diluted HCl (1 : 9), and finally eight to ten times with hot water, then ignite at a red heat and weigh as the insoluble residue.

403. A.S.T.M. Method for Determining Sulphuric Anhydride.—

10. Add 25 ml. of cold water and 5 ml. of HCl (sp. gr. 1.19) to a 1-g. sample of cement. Heat the solution and grind the material with the flattened end of a glass rod until it is evident that decomposition of the cement is complete. Dilute the solution to 50 ml. and digest on a steam bath for 15 min., filter, and wash the residue thoroughly with hot water. Dilute the solution to 250 ml., heat to boiling, add slowly, drop by drop from a pipette, 10 ml. of a hot barium chloride solution (10 per cent), and continue the boiling until the precipitate is well formed. Then digest the solution on the steam bath for at least 3 hr., preferably overnight. Filter the precipitate, wash and place the paper and contents in a weighed platinum crucible and slowly char and consume the paper without flaming. Then ignite, and weigh the barium sulphate. The weight obtained multiplied by 34.3 gives the percentage of sulphuric anhydride. The acid filtrate obtained in the determination of the insoluble residue may be used for the estimation of sulphuric anhydride instead of using a separate sample.

404. A.S.T.M. Method for Determining Silica.—

11. (*a*) Transfer a 0.5-g. sample of the finely powdered cement to an evaporating dish, preferably of platinum for the sake of celerity in evaporation, moisten with 10 ml. of cold water to prevent lumping, add 5 to 10 ml. of HCl (sp. gr. 1.19) and digest with the aid of gentle heat and agitation until solution is complete. Solution may be aided by light pressure with the flattened end of a glass rod. Evaporate the solution to dryness on a steam bath. Treat the residue without further heating at first with 5 to 10 ml. of HCl (sp. gr. 1.19) then diluting to half strength or less, or pour at once upon the residue a larger volume of acid of half strength. Then cover the dish and digest for 10 min. on the bath or a hot plate. Dilute the solution with an equal volume of hot water, immediately filter, and wash the separated silica thoroughly with hot water and reserve. Again evaporate the filtrate to dryness, baking the residue in an oven 1 hr. at a temperature of 105 to 110° C. Then take up the residue with 10 to 15 ml. of diluted HCl (1 : 1) and heat on the bath or hot plate. Dilute the solution with an equal volume of hot water and catch and wash the small amount of silica it contains on another filter paper. Reserve the filtrate and washings. Transfer this paper and the reserved paper containing the residues to a weighed platinum crucible, dry, ignite first over a bunsen burner until the carbon of the filter paper is completely consumed without flaming and finally over a burner or in an electric oven at 1100 to 1200° C. until the weight remains constant.

(*b*) Treat the silica thus obtained, which will contain small amounts of impurities, in the crucible with a few drops of water, about 10 ml. of HF and one drop of H_2SO_4, and evaporate to dryness over a low flame. Finally, heat the small residue at 1050 to 1100° C. for a minute or two, cool, and weigh. The difference between this weight and the weight previously obtained represents the amount of silica. Washing of the silica precipitates can be made more effective by using a hot solution of diluted HCl (1 : 99), *and then completing* the washing with hot water. Consider the weighed residue, *remaining after* volatilization of the silica, as combined aluminum and ferric oxides and add it to the result obtained in the determination of these oxides (Section 12).

405. A.S.T.M. Method for Determining Ferric Oxide and Alumina.—

12. Treat the reserved filtrate (Note 1), which should have a volume of about 250 ml. with HCl, if necessary, to insure a total of 10 to 15 ml. of the acid, add a few drops of methyl red indicator and then heat to boiling. Then treat with NH_4OH (Note 2), drop-by-drop, until one drop changes the color of the solution to a distinct yellow. Bring to boiling the solution containing the precipitated iron and aluminum hydroxides, boil for 1 or 2 min., and then filter. Wash the precipitate once by decantation and slightly on the filter with a hot ammonium nitrate solution (2 per cent). Set aside the filtrate and transfer the precipitate and filter paper to the same beaker in which the first precipitation was effected. Then dissolve the iron and aluminum hydroxides in hot diluted HCl (1 : 3), make up the solution to about 100 ml., and reprecipitate the hydroxides as in the first case. Then filter the solution and wash the precipitate with two 10-ml. portions of a hot ammonium nitrate solution (2 per cent). Combine the filtrate and washings with that set aside and place the precipitate in a weighed platinum crucible, slowly heat by a bunsen or Meker burner until the papers are charred, and finally ignite to constant weight at 1050 to 1100 C. with care to prevent reduction, and weigh as $Al_2O_3 + Fe_2O_3$.

Note 1.—If a platinum evaporating dish has been used for the dehydration of silica, iron may have been partially reduced. At this stage, add about 3 ml. of saturated aqueous solution of bromine to the filtrate and boil the filtrate to eliminate the excess bromine before adding the methyl red indicator.

Note 2.—The NH_4OH used to precipitate the hydroxides must be free of contamination with carbon dioxide.

Ferric Oxide.—The result for this method for determining ferric oxide is not affected by any titania or vanadium oxide that may be in the cement. It is therefore understood that these are counted as Al_2O_3 in this method. If the precipitations of aluminum and iron are made as directed, little if any manganese will be retained in the precipitate.

13. *Solutions Required.*—The following solutions will be required:

(*a*) *Stannous Chloride.*—Dissolve 2 g. of the crystallized salt in ten times its weight of a mixture of three parts of water and one of HCl (sp. gr. 1.19). Add scraps of iron-free granulated tin and boil until the solution is clear. Keep the solution in a closed dropping bottle containing metallic tin.

(*b*) *Phosphoric Acid Mixture.*—Add slowly and with stirring 150 ml. of orthophosphoric acid (sp. gr. 1.71), and 150 ml. of H_2SO_4 (sp. gr. 1.84), to 500 ml. of water and then dilute to 1000 ml. with water and mix.

(*c*) *Diphenylamine Indicator.*—Dissolve 1 g of diphenylamine in 100 ml. of H_2SO_4 (sp. gr. 1.84).

(*d*) *Standard Potassium Bichromate Solution.*—Dissolve 2.457 g. of $K_2Cr_2O_7$ in distilled water and dilute to 1 liter. Standardize against standard iron wire of known iron content in the same manner as directed for the ferric oxide determination in cement (Section 14), using a weight of iron wire which will yield a titration approximately equal to that required by the cement sample in question.

14. *Method.*—Add 20 ml. of cold water and 10 ml. of HCl (sp. gr. 1.19) to a 1-g. sample of cement. Heat the solution and grind the material with the flattened end of a glass rod until it is evident that decomposition of the cement is complete. Dilute the solution to 50 ml. and heat to boiling. Then treat the solution with 5 ml. of HCl (sp. gr. 1.19) and then with a solution of stannous chloride, added drop by drop while stirring until the solution is decolorized, then add one drop more. Cool the solution to

room temperature, rinse the inside of the vessel with water and add all at once 10 ml. of a cool saturated solution of mercuric chloride. Then stir the solution vigorously for 1 min., treat with 15 ml. of phosphoric acid mixture and three drops of diphenylamine indicator and dilute to 150 ml. with cold water. Then titrate with a standard potassium dichromate solution having a titer no greater than 0.004 g. of Fe_2O_3. The end point is taken as the point when a drop causes an intense deep-blue coloration that remains unchanged on the further addition of the standard $K_2Cr_2O_7$ solution.

406. A.S.T.M. Method for Determining Calcium Oxide.—

15. Add a few drops of NH_4OH to the combined filtrates obtained in the alumina and ferric oxide precipitation (Section 12) and bring the solution to boiling. Add to the boiling solution 25 ml. of a boiling ammonium oxalate solution (5 per cent), the boiling being continued until the precipitated calcium oxalate assumes a well-defined granular form. Then allow the solution to stand for about 20 min. or until the precipitate has settled, filter, and moderately wash with an ammonium oxalate solution (0.1 per cent). Reserve the filtrate and washings. Place the filter paper containing the precipitate, wet, in a platinum crucible and burn off the paper over the small flame of a bunsen burner. Then ignite the precipitate until the oxalate is converted to oxide (Note), redissolve in HCl and make up the solution to 100 ml. with water. Add NH_4OH in slight excess and bring the solution to boiling. If a small amount of alumina separates at this point, filter it out, weigh, and add the amount to that found in the original alumina determination. Then reprecipitate the lime by ammonium oxalate, allow to stand until settled, filter, and wash, taking care to avoid an excess of the washing solution. Combine the filtrate with that already reserved. Weigh the precipitate as calcium oxide after ignition and blasting to constant weight in a weighed, covered platinum crucible.

NOTE.—If the ignited precipitate is darkly colored, it may contain an appreciable amount of manganese. The contamination of the second precipitate of calcium oxalate by manganese should be as low as possible. The following procedure may be used to reduce the contamination: add 5 ml. of cold water cautiously to the precipitate and then cautiously add 10 ml. of diluted HCl (1 : 1). Heat the mixture. If the resulting solution is colored, digest it on the hot plate gently for 10 min. or longer until the color disappears or until it is apparent the color will not become lighter on further heating. After a little practice it is possible to dissolve hard-burnt lime in this way without explosive spattering.

If the second precipitate of calcium oxalate is so fine as to cause difficulty in filtering or if the precipitate causes bumping, the volume of solution may be increased to 150 or 200 ml., instead of 100 ml., prior to precipitation.

407. A.S.T.M. Method for Determining Magnesia.*—

In this method for determining magnesia, most of any manganese in the cement is precipitated with the magnesium. It is understood in this method that manganese so precipitated shall be calculated as magnesium.

16. Acidify the filtrates reserved in the determination of calcium oxide (Section 15) with HCl and concentrate to about 150 ml. Add to this solution about 10 ml. of diammonium phosphate solution (25 g. of the salt per 100 ml. of water) and boil the solution for several minutes. Then cool the solution by placing in a beaker of ice water. After cooling, add NH_4OH drop by drop, while stirring constantly, until the crystalline ammonium-magnesium orthophosphate begins to form, and then in moderate excess (5 to 10 per cent of the volume of the solution), the stirring being continued for several minutes. Set the solution aside for at least 8 hr. in a cool atmosphere, and then filter. Redissolve the precipitate thus obtained in hot diluted HCl (1 : 4), make up the solution to about 100 ml., add 1 ml. of the solution of diammonium phosphate, and NH_4OH

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* The Standard Methods for Rapid Determination of Magnesia in Portland Cement (Alternate Methods) (A.S.T.M. Designation C 77–38) supplement the chemical determinations of these methods and appear in the 1938 Supplement to Book of A.S.T.M. Standards, p. 100.

drop by drop, while stirring constantly until the precipitate is again formed as described, and the ammonia is in moderate excess. Then cool, allow to stand for about 2 hr., filter, and wash with two 10-ml. portions of wash solution (200 ml. of concentrated NH_4OH, 100 g. of ammonium nitrate, and 800 ml. of water), place in a weighed platinum crucible, slowly char the paper, and carefully burn off the resulting carbon. Ignite the precipitate at a temperature between 1100 and 1200° C. to constant weight, taking care to avoid bringing the pyrophosphate to melting. The weight of magnesium pyrophosphate obtained multiplied by 72.4 gives the percentage of magnesia.

Blank Determination.—17. Make a blank determination of sulphuric anhydride, silica, ferric oxide and alumina, ferric oxide, calcium oxide, and magnesia, using the same procedures as outlined in Sections 8 to 16, and using approximately the same amounts of reagents. Correct accordingly the results previously determined.

Balances.—18. The balances used in the chemical determinations shall conform to the following requirements:

(*a*) Capacity not less than 100 g. in each pan;

(*b*) The two arms of beam to be equal to within one part in 100,000;

(*c*) Capable of reproducing results within 0.1 mg.;

(*d*) "Sensibility reciprocal" * not more than 0.2 mg. per division of the graduated scale.

(*e*) The weights used in the chemical determinations shall conform to the requirements of the National Bureau of Standards specifications for Class "S" weights as contained in Bureau of Standards *Circular No. 3.*

408. Purity Test.—The so-called purity test affords a speedy determination of the presence of adulterants. The test may be made as follows: Place about one-half teaspoonful of cement in a test-tube. Stir the cement with a glass rod and cover with a 50 per cent solution of hydrochloric acid. If the cement is pure, it will effervesce slightly and form a yellow or orange-yellow jelly; the presence of an adulterant consisting mainly of calcium carbonate will cause violent effervescing. Slag will cause the emission of sulphuretted hydrogen; other insoluble adulterants form a dark sediment at the bottom of the jelly.

PHYSICAL TESTS

409. Determination of Specific Gravity.—In order to determine the density of mortar or concrete, the specific gravity of the cement must be known. The specific gravity test is also useful in detecting adulteration. The former standard method, here presented, may also be used on sand or other fine powders.

Apparatus.—The determination of specific gravity shall be made with a standardized Le Châtelier apparatus which conforms to the requirements illustrated in Fig. 2. This apparatus is standardized by the United States Bureau of Standards. Kerosene free from water, or benzine not lighter than 62° Baumé, shall be used in making this determination.

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* The sensibility reciprocal is a measure of the sensitivity of a balance, and is the weight required to move the position of equilibrium of the beam, pan, pointer, or other indicating device of a scale a definite amount at the capacity or at any lesser load. For a complete definition of sensibility reciprocal, see Bureau of Standards *Handbook, M 85*, pp. 80–82.

Method.—The flask shall be filled with either of these liquids to a point on the stem between zero and 1 cc., and 64 g. of cement, of the same temperature as the liquid, shall be slowly introduced, care being taken that the cement does not adhere to the inside of the flask above the liquid and to free the cement from air by rolling the flask in an inclined position. After all the cement is introduced, the level of the liquid will rise to some division of the graduated neck; the difference between readings is the volume displaced by 64 g. of the cement.

The specific gravity shall then be obtained from the formula

$$\text{Specific gravity} = \frac{\text{Weight of cement (g)}}{\text{Displaced volume (cc.)}}.$$

The flask, during the operation, shall be kept immersed in water, in order to avoid variations in the temperature of the liquid in the flask, which shall not exceed 0.5°C. The results of repeated tests should agree within 0.01.

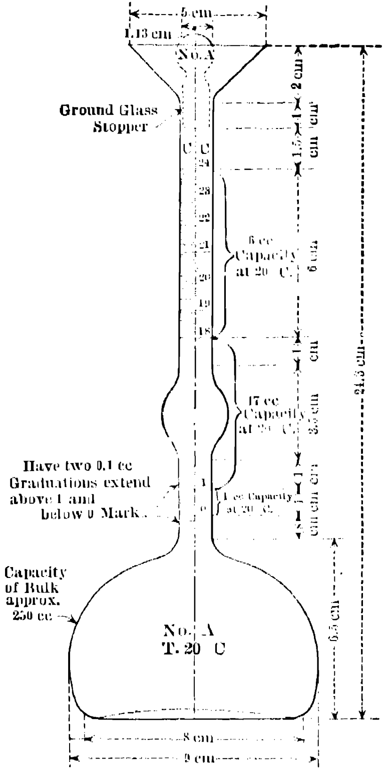

Fig. 2.—Le Châtelier Apparatus.

Fineness

410. A.S.T.M. Method.—

Apparatus.—19. *Sieves.*—Wire cloth for standard sieves for cement shall be woven (not twilled) from brass, bronze, or other suitable wire, and mounted without distortion on frame about 2 in. below the top of the frame. The joint between the cloth and frame shall be smoothly filled with solder to prevent lodging of the cement. The sieve frame shall be circular, approximately 8 in. in diameter, and shall be provided with a pan and cover.

20. *No. 200 Sieve.*—A standard No. 200 sieve is one having nominally a 0.0029-in. opening, certified by the National Bureau of Standards, and conforming to the specifications for this sieve in the Tentative Specifications for Sieves for Testing Purposes (A.S.T.M. Designation: E 11) of the American Society for Testing Materials.* The correction to the sieving value of the sieve shall be determined by sieving tests made in conformity with the standard specifications for these tests using a cement standardized for fineness.

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* *Proceedings*, Am. Soc. Testing Mats., Vol. 38, Part I (1938); also 1938 Book of A.S.T.M. Tentative Standards, p. 1607.

21. *Balances.*—The balance used in making the fineness test shall conform to the following requirements: The balance shall be enclosed in a glass case. On balances in use the tolerance at a load of 50 g. shall be ±0.05 g., and at loads less than 0.1 g. the tolerance shall be ±0.01 g. The tolerances on new balances shall be one-half of these values.

The maximum sensibility reciprocal (see footnote, Section 18) allowable at each of the loads specified above shall be twice the value of the tolerance specified for the load in question.

The tolerances on the weights in use in the fineness test shall be as follows:

Weight	Tolerance	Weight	Tolerance
50 g.	±0.04 g.	0.500 g.	±0.003 g.
20 g.	±0.02 g.	0.200 g.	±0.002 g.
10 g.	±0.014 g.	0.100 g.	±0.001 g.
5 g.	±0.010 g.	0.050 g.	±0.001 g.
2 g.	±0.006 g.	0.020 g.	±0.001 g.
1 g.	±0.004 g.	0.010 g.	±0.001 g.

The tolerances on new weights shall be one-half of these values.

Method.—22. The fineness test shall be made with 50 g. of cement. The sieve shall be thoroughly clean and dry. The cement shall be placed on the No. 200 sieve. The sieve, with pan and cover attached, shall be held in one hand in a slightly inclined position so that the sample will be well distributed over the sieve, at the same time gently striking the side about 150 times per minute against the palm of the other hand on the up stroke. The sieve shall be turned every 25 strokes about one-sixth of a revolution in the same direction. The operation shall be continued until not more than 0.05 g. passes through in 1 minute of continuous sieving.

The fineness shall be determined from the weight of the residue on the sieve expressed as a percentage of the weight of the original sample, applying the sieve correction.

23. Washers, shot and slugs shall not be used on the sieve.

Mechanical Sieving.—24. Mechanical sieving devices may be used, but the cement shall not be rejected if it meets the fineness requirement when tested by the hand method described in Section 22.

411. Accuracy in Fineness Tests.—A skillful operator should check himself within 1 per cent when using the same sieve and cement. Sieves with correction factors certified by the U. S. Bureau of Standards can be procured from manufacturers. The Bureau also can furnish cements of certified fineness so that a laboratory can calibrate and periodically check its sieves. Sieves with correction factors less than ±2 per cent should be used on important determinations.

412. Mechanical Shakers.—In spite of the fact that hand sieving is given preference in the specifications a number of mechanical sifting devices are being used with satisfaction.

In operating such shakers it is customary to sift the cement for a certain time at a given rate. This method does not give results which agree with those recommended by standard specifications since different cements will pass through the sieves at different time rates.

If the method recommended by the A.S.T.M. for hand shaking be followed, little time will be gained unless the shaker is made to accommodate several sets of sieves and pans. The Hunt shaker manufactured by the

Humboldt Manufacturing Company, Chicago, carries four 8-in. diameter sieves and well reproduces the rotary and tapping motion of hand sieving. Twenty minutes is a satisfactory shaking period for this apparatus, but any or all of the sieves may be removed at any time without stopping the shaker.

A shaker recently developed by the W. S. Tyler Co. of Cleveland is shown in Fig. 3. This device is so designed that six 8-in. standard sieves or 13 half-height sieves may be shaken at one operation. The driving mechanism is arranged to rotate the sieves and tap them 150 times a minute. By using the time switch, shown at the right, the shaker may be automatically stopped at the end of a predetermined period, 20 minutes usually being sufficient.

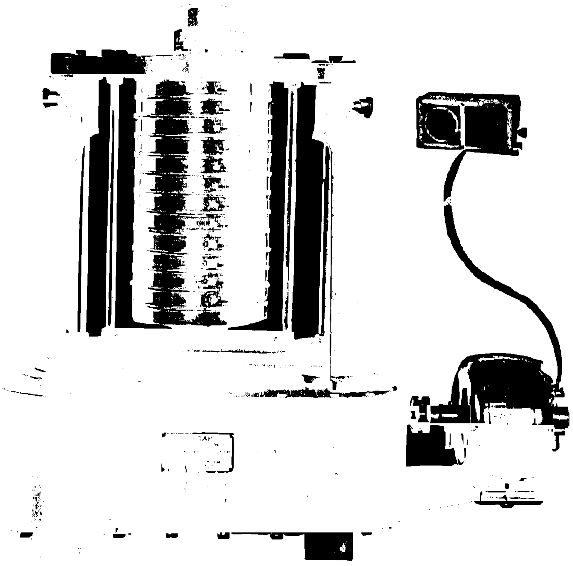

FIG. 3.—A Ro-tap Mechanical Shaker Equipped with a Stop-Rite Time Switch.

413. Other Methods of Determining Fineness.*—Since in tests of Portland cements residues on the No. 200 sieve are usually 12 per cent or less, the limitation based on that sieve is no longer a standard requirement in the A.S.T.M. specifications. Sieves finer than No. 200 are so expensive and difficult to standardize that recourse is being made to other means for determining the particle-size distribution of Portland cements. A good description of a number of air separators, including the Pearson analyzer perfected at the U. S. Bureau of Standards, is given in *Technologic Paper* No. 48. With this type of device it is possible to separate particles of 0.0004 in. diameter, or less, which constitute about a fourth to a third of normal Portland cements.

At the Bureau of Standards there has also been developed a turbidimeter,† by which the surface area of a known fraction of a gram of cement is estimated. This is accomplished by dispersing the cement in a uniform manner in a rectangular glass tank filled with kerosene, passing parallel light rays through the solution onto the sensitive plate of a photoelectric cell. The turbidity of the solution at a given instant is measured by taking readings of the current generated by the cell. By taking such readings at regular intervals while the particles are falling in the solution it is possible to secure information regarding the grading in surface area and in size of particle. Readings are usually expressed in square centimeters per gram of cement. For procedure in using this turbidimeter, see A.S.T.M. Standards, Des. C115–42.

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* See A.S.T.M. Standards, Des. C184–44, C204–46T, and C115–42.

† See papers by L. A. Wagner, *Proc.*, *A.S.T.M.*, Vol. 33, Pt. 2, p. 553; also by H. S. Ponzer and D. R. Mac Pherson, Vol. 38, Pt. 2, p. 441.

Mixing Cement Pastes and Mortars

414. A.S.T.M. Method.—

Apparatus.—25. The scales used in weighing materials for neat cement and mortar mixes shall conform to the following requirements: On scales in use the tolerance at a load of 1000 g. shall be ±1.0 g. The tolerance on new scales shall be one-half of this value. The sensibility reciprocal (see footnote, Section 18) shall not be greater than twice the tolerance.

The tolerances on the weights in use in weighing materials for neat cement and mortar mixes shall be as follows:

Weight	Tolerance	Weight	Tolerance
1000 g.	±0.5 g.	100 g.	±0.15 g.
900 g.	±0.45 g.	50 g.	±0.10 g.
750 g.	±0.4 g.	20 g.	±0.05 g.
600 g.	±0.35 g.	10 g.	±0.04 g.
300 g.	±0.3 g.	5 g.	±0.03 g.
250 g.	±0.25 g.	2 g.	±0.02 g.
200 g.	±0.20 g.	1 g.	±0.01 g.

The tolerances on new weights shall be one-half these values.

Glass Graduates.—26. Glass graduates of 100-ml. to 200-ml. capacities used for measuring the mixing water shall be made to deliver the indicated volume at 20° C. (68° F.). The tolerance on these graduates shall be ±1.0 ml.

Method of Mixing.—27. The quantities of dry materials to be mixed at one time shall be 500 g. for neat cement mixtures and not less than 1000 g. nor more than 1200 g. for mortar mixtures. The proportions of cement or cement and sand shall be stated by weight in grams of the dry materials; the quantity of water shall be expressed in milliliters. The dry materials shall be weighed, placed upon a smooth non-absorbent surface, thoroughly mixed dry if sand is used, and a crater formed in the center, into which the proper percentage of clean water shall be poured; the material on the outer edge shall be turned into the crater within 30 seconds by the aid of a trowel. After an additional interval of 30 seconds for the absorption of the water the operation shall be completed by continuous, vigorous mixing, squeezing and kneading with the hands for 1½ minutes. During the operation of mixing, the hands shall be protected by rubber gloves.

Temperature.—28. The temperature of the room and dry materials shall be maintained at not less than 20 C. (68° F.) and not more than 27.5° C. (81.5° F.). The temperature of the mixing water, moist closet, and water in the briquet storage tank shall not vary from 21 C. (70° F.) more than 1.7 C. (3° F.).

415. Additional Recommendations.—Mixing tables should be about 34 to 36 in. above the floor, depending upon height of operator. For a mixing surface, a ¼-in., cold-rolled steel plate is satisfactory. Tables should be well lighted and not exposed to changes of temperature or drafts. Table, balance weights, and tools should be kept clean. A dispensing burette of 200-cc. capacity, fastened at a convenient height, will be found satisfactory for measuring the water. If a graduate is used it should have a rubber guard around the top to prevent breakage. Rubber gloves should be comfortable and flexible. They should not be wetted prior to mixing. Dry mixing should be thoroughly done with a trowel. Only water suitable for drinking should be used, and it should be accurately measured. Evaporation losses can be avoided if the crater is made sufficiently large and care is taken to keep the water inside the crater during the operations of absorption and mixing.

416. Kneading.—The practice frequently employed in kneading is as follows: The operator covers the pile of material with his hands placed palms downward with fingers pointing away from him. He then quickly forces the wrists forward keeping the ends of the fingers fixed and exerting a downward pressure of about 20 lb. with the palms. After three or four similar movements the pile is turned through an angle of 90 degrees, any loose material gathered in and the above manipulation repeated. The pile should be given twenty to twenty-five turns in a minute.

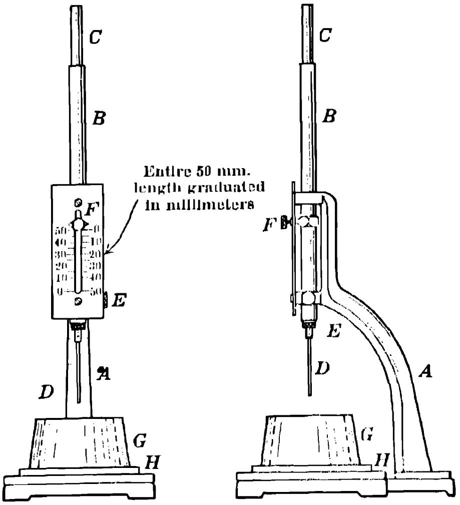


FIG. 4.—Vicat Apparatus.

NORMAL CONSISTENCY

417. A.S.T.M. Method.

Apparatus.—29. The Vicat apparatus shall consist of a frame *A* (Fig. 4) bearing a movable rod *B*, weighing 300 g., one end *C*, the plunger end, being 1 cm. in diameter for a distance of at least 5 cm., the other end having a removable needle *D*, 1 mm. in diameter and 5 cm. long. The rod *B* is reversible, and can be held in any desired position by a screw *E*, and has an adjustable indicator *F* which moves over a scale (graduated to millimeters) attached to the frame *A*. The paste is held in a rigid conical ring *G*, resting on a glass plate *H* about 10 cm. square. The ring shall be made of a non-corroding, non-absorbent material, and shall have an inside diameter of 7 cm. at the base, 6 cm. at the top, and a height of 4 cm.

In addition to the above, the Vicat apparatus shall conform to the following requirements:

Weight of plunger	300 g.	± 0.5 g.	(0.661 lb. ± 8 grains)
Diameter of larger end of plunger	1 cm.	± 0.005 cm.	(0.394 in. ± 0.002 in.)
Diameter of needle	1 mm.	± 0.05 mm.	(0.039 in. ± 0.002 in.)
Inside diameter of ring at bottom	7 cm.	± 0.3 cm.	(2.75 in. ± 0.12 in.)
Inside diameter of ring at top	6 cm.	± 0.3 cm.	(2.36 in. ± 0.12 in.)
Height of ring	4 cm.	± 0.1 cm.	(1.57 in. ± 0.04 in.)
Graduated scale	The graduated scale, when compared with a standard scale accurate to within 0.1 mm. at all points, shall not show a deviation at any point greater than 0.25 mm.		

Method.—30. *Normal Consistency, Neat Cement.*—In making the determination, 500 g. of cement, with a measured quantity of water, shall be kneaded into a paste, as described in Section 27, and quickly formed into a ball with the gloved hands, completing the operation by tossing it six times from one hand to the other, maintained about 6 in. apart; the ball resting in the palm of one hand shall be pressed into the larger end of the conical ring *G*, Fig. 4, held in the other hand, completely filling the ring with paste; the excess at the larger end shall then be removed by a single movement of the palm of the hand; the ring shall then be placed on its larger end on a glass plate *H*, and the excess paste at the smaller end sliced off at the top of the ring by a single oblique stroke of a sharp-edged trowel held at a slight angle with the top of the ring, and the top smoothed, if necessary, with a few light touches of the pointed end of the trowel. During these operations care shall be taken not to compress the paste. The paste confined in the ring, resting on the plate, shall be centered under the rod *B*, Fig. 4, the plunger end *C*, of which shall be brought in contact with the surface of the paste and the set-screw *E* tightened. Then the movable indicator *F* shall be set to the upper zero mark of the scale or an initial reading taken and the rod released 30 seconds after completion of mixing. The apparatus shall be free from all vibrations during the test.

TABLE 1.—PERCENTAGE OF WATER FOR STANDARD MORTARS.

Percentage of Water for Neat Cement Paste of Normal Consistency	Percentage of Water for Mortar of One Cement, Three Standard Ottawa Sand[a]	Percentage of Water for Neat Cement Paste of Normal Consistency	Percentage of Water for Mortar of One Cement, Three Standard Ottawa Sand[a]
15	9.0	23	10.3
16	9.2	24	10.5
17	9.3	25	10.7
18	9.5	26	10.8
19	9.7	27	11.0
20	9.8	28	11.2
21	10.0	29	11.3
22	10.2	30	11.5

[a] When the proportions of cement to sand are other than one to three by weight, the amount of mixing water shall be calculated from the following formula, upon which Table 1 is based:

$$y = \frac{2}{3}\frac{P}{n+1} + K$$

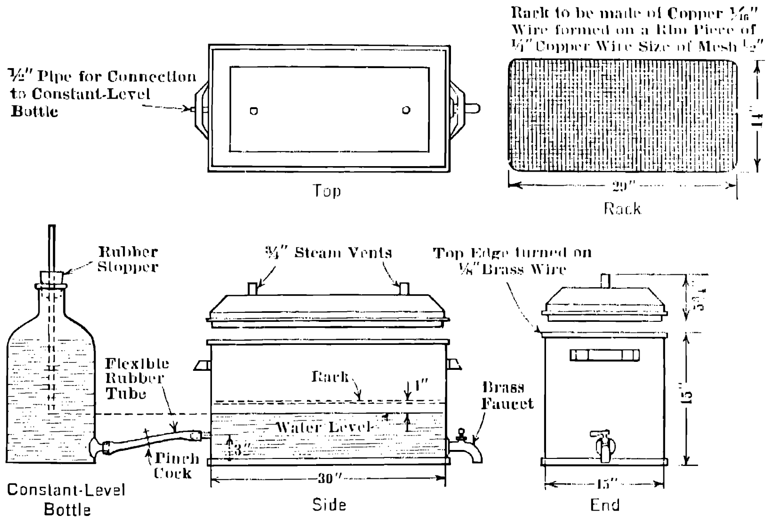
where y = the percentage of water required for the sand mortar,
P = the percentage of water required for neat cement paste of normal consistency,
n = the number of parts of sand to one of cement by weight, and
K = a constant which for standard Ottawa sand has the value 6.5.

The paste shall be of normal consistency when the rod settles to a point 10 mm. below the original surface in 30 seconds after being released. Trial pastes shall be made with varying percentages of water until the normal consistency is obtained. Each trial shall be made with fresh cement. The amount of water required shall be expressed in percentage by weight of the dry cement.

31. *Normal Consistency, Standard Mortar.*—The consistency of standard mortar shall depend on the amount of water required to produce a paste of normal consistency from the same sample of cement. Having determined the normal consistency of the cement sample, the consistency of standard mortar made from the same sample shall be as indicated in Table 1, the values being in percentage of the combined dry weights of the cement and standard sand.

418. Hints on Determinations of Consistency.—The Vicat apparatus must be kept clean, well oiled, and in standard condition. Final determinations should be made on fresh batches without remixing or retempering. If this most important determination is to be made properly, not only must care be exercised in mixing and placing the paste to follow standard procedure, but also the specimen must be centered beneath the plunger in testing.

For cements with a flash set *an approximation* of the proper amount of water can be had by the *ball method.* A 2-in. ball of properly molded paste is dropped from a height of 2 ft. upon the mixing table. For normal consistency the ball should flatten not more than one-half of its diameter without cracking.


½" Pipe for Connection to Constant-Level Bottle
Top
Rack to be made of Copper ⅟₁₆" Wire formed on a Rim Piece of ¼" Copper Wire Size of Mesh ½"
11"
29"
Rack
Rubber Stopper
¾" Steam Vents
Top Edge turned on ⅛" Brass Wire
3¼"
Flexible Rubber Tube
Rack
1"
Brass Faucet
15"
Water Level
3"
Pinch Cock
30"
15"
Constant-Level Bottle
Side
End

Apparatus to be made of Sheet Copper weighing 22 oz. per sq. ft. tinned inside. All seams to be lapped where possible. Hard solder only to be used. Dimensions are optional except distance between water level and top of rack which must be 1 inch as specified.

FIG. 5.—Apparatus for Making Soundness Test of Cement.

SOUNDNESS

419. A.S.T.M. Method.—

Apparatus.—32. A steam apparatus, which can be maintained at a temperature between 98 and 100° C., or one similar to that shown in Fig. 5, is recommended. The capacity of this apparatus may be increased by using a rack for holding the pats in a vertical or inclined position.

Method.—33. A pat from cement paste of normal consistency about 3 in. in diameter, ½ in. in thickness at the center, and tapering to a thin edge, shall be made on a flat, clean glass plate about 4 in. square. In molding the pat, the cement paste shall first be flattened on the glass and the pat then formed by drawing the trowel from the outer edge toward the center to give a rounded surface. The pats used for the time of setting tests by the Gillmore method (Section 40) may be used for soundness tests. After making, pats shall be stored in the moist closet for 24 hours.

34. The pat on the glass plate shall then be placed in an atmosphere of steam at a temperature between 98 and 100° C., upon a suitable support 1 in. above boiling water for 5 hours.

Soundness.—35. The pat shall be examined for unsoundness within 1 hour after removal from the steam apparatus. Unsoundness is usually manifested by change in volume which causes distortion, cracking, checking, or disintegration, as illustrated in Fig. 6 (*b*).

Should the pat leave the plate, distortion may be detected best with a straight edge applied to the surface which was in contact with the plate.

420. Hints on Manipulation.—Since soundness is the most important property of a cement, care must be exercised in all determinations to avoid errors which will influence the results of this test. Clean, dry, glass plates, free from oil, should be used. Batches should be of normal consistency and contain not less than 500 grams of cement, as specified. Shortening the standard 24-hour storage period in the moist closet may cause an unsound cement to pass the test. From time to time check determinations should be made on the temperatures in the steaming device.

Speed in roughly molding the pats may be gained by rapidly tapping the glass plate supporting the paste on the bench. This action quickly spreads the paste into a flat circular pile and at the same time expels the air entrapped between the plate and pat. A common fault with the unexperienced operator is to make the pat too wet or to allow it to dry by standing on the bench. Either of these errors is liable to cause shrinkage cracks. In marking the pats, deep abrasions of the surface should be avoided for similar reason.

421. Le Châtelier's Test for Soundness.—Several other accelerated tests for soundness have been devised. One of these, which was recommended by the Committee on Accelerated Tests of the International Association for Testing Materials * and specified in both the British and French Standard Specifications, is the rough measurement of the expansion of a cylindrical test piece by Le Châtelier's tongs, shown in Fig. 7. The method of making the test, which was originally proposed by Le Châtelier and adopted by the committee, follows: "The cement is gaged and filled into a mold on a plate of glass, the edges of the mold being held together. When the mold has been filled it is covered with a

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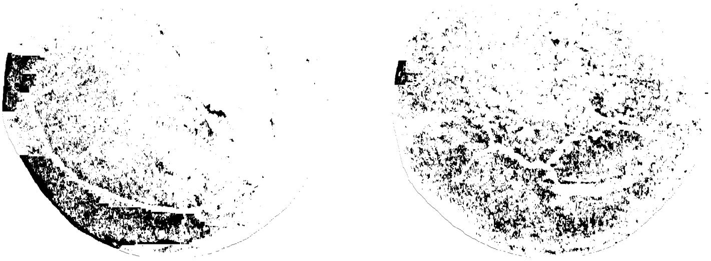
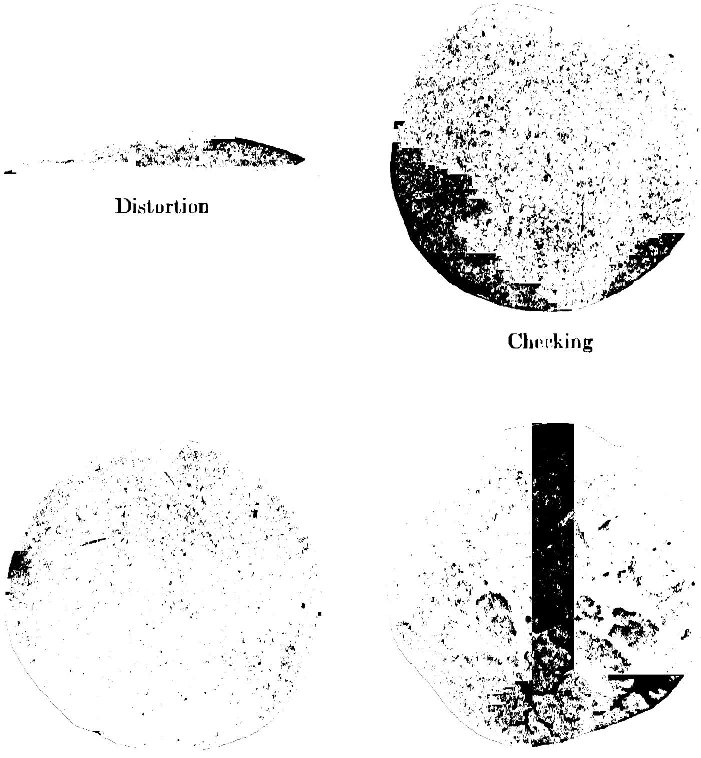
* See *Proc. I.A.T.M.*, 5th Congress, 1909 X_3; also *Engr. News*, Vol. 68, p. 506.



(*a*) Shrinkage Cracks Due to Exposure of Pats to Dry Air During Setting.



Distortion

Checking

Cracking

Disintegration

(*b*) Typical Failures in Soundness Test.

Fig. 6.—Soundness Test Pats.

plate of glass held down by a small weight and the whole is immersed in water at 15° C. for twenty-four hours. Any tie or band which has been used to keep the edges of the mold together during setting is then removed. The distance between the indicator needles is measured and the mold is placed in cold water, which is raised to a temperature of 100° C. in the course of half an hour and is kept boiling for six hours. The mold is removed from the water and after it has cooled the distance between the indicator needles is again measured. The difference between the two measurements represents the expansion of the cement. This must not exceed 10 mm. when the cement has been aerated for twenty-four hours and 5 mm. when the cement has been aerated for seven days."

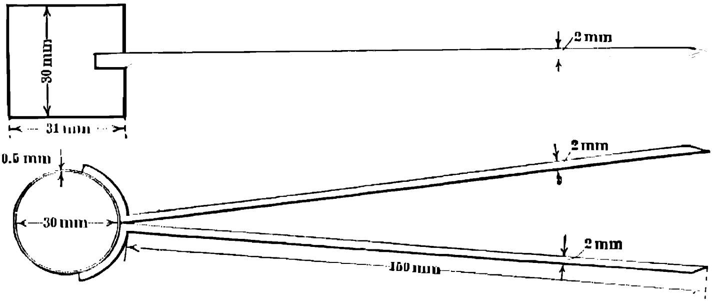


FIG. 7.—Le Châtelier's Tongs for Testing Constancy of Volume of Cement Pastes.

422. The Boiling Test.—The boiling test recommended in 1870 by Dr. Michaelis has been considerably used for detecting unsoundness. In making this test a 2-in. ball of neat cement paste of standard consistency is allowed to harden in the moist closet for 24 hr., or longer if hard set has not been obtained. It is then placed in a pan of pure water at normal room temperature. The temperature of the water is gradually raised to the boiling-point in not less than 30 min. After boiling for 3 hr. the ball is removed, allowed to cool without sudden chilling, then examined for signs of disintegration.

423. The Autoclave Test.*—A still more stringent accelerated test † has been used by the Portland Cement Association and may eventually displace the pat test. In this test two or more neat cement prisms 1 by 1 by 11¼ in. long are molded from paste of normal consistency and provided with ¼ by ⅝-in. stainless-steel reference points centered in each end. The paste is placed in the mold in two layers and tapped 100 times with the glove-covered forefinger as it is moved forward and backward along the mold twice. After the top layer has been compacted it is cut off flush, and the surface smoothed with the trowel. After 24 hr. in the moist closet specimens are removed from molds and measured for length at 70° F. in a dial comparator reading to 0.0001 in. They are then placed in an autoclave. In the course of an hour, the steam pressure is raised to 295 lb./in.^{2} (420° F.) and held constant for 3 hr. Then the autoclave is gradually cooled until the pressure is 10 lb./in.^{2} or less in an hour. Specimens are then removed and placed in boiling water, which is cooled in 15 min. to 70° F., when they are surface-dried and again measured.

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* Now a standard. See A.S.T.M. Standards, Des. C151–43.

† For test procedure of Committee C 1, see *Proc. A.S.T.M.*, Vol. 38, Pt. I, p. 297; for Force's tests, see *Engr. News*, Vol. 67, p. 1111 and p. 1136; Vol. 68, p. 80; Vol. 69, p. 185; Vol. 70, pp. 40, 82, 277; *Proc. A.S.T.M.*, Vol. 14, p. 246.

Since the action of the autoclave causes a rapid hydration of either free lime or free magnesia, the expansion measurements furnish a clue to the expansive effects of these elements. The autoclave test is far more drastic than the pat test. Indeed it is essential that more correlation be obtained between the expansion of mortars of unsound cements under moist curing and in the autoclave before definite limits are established for the autoclave test. For the present, a Portland cement exhibiting in this test an expansion of 1 per cent or more should be viewed as unsatisfactory.

424. The Value of the Soundness Test.—The standard accelerated soundness test is useful in detecting unsoundness caused by the hydration of finely ground free lime. Lerch, after confirming the foregoing statement, in *P.C.A. Fellowship Paper* No. 20, states that the amount of free lime necessary to cause unsoundness may vary with different cements; that a cement with less than 1 per cent of free lime will usually be sound, whereas a cement having 3 per cent or more is likely to be unsound.

If a cement contains free lime which is coarsely ground and highly burned, it is doubtful if the standard test will always reveal the unsoundness. (See *Technologic Paper* No. 43, p. 58.) It is contended, however, that the autoclave test will. Extensive tests made by the Bureau of Standards (*Technologic Paper* No. 47) on the cements which passed and failed in the autoclave test and on concretes made from them did not show that the strength of the concrete made from cements which failed in the autoclave was materially affected after a 2-yr. curing out of doors.

From the results of Prof. E. D. Campbell,* it appears that the standard steam pat test does not always detect free magnesia. His tests show that only 4 per cent of free magnesia is needed to cause water-cured cement prisms to expand linearly over 2 per cent.

That the autoclave test is a valuable criterion of the expansive influences of magnesia in moist-cured mortars is evidenced in the tests by Withey and Wendt.† Its value in indicating the influence of free lime is shown in Young's tests.‡ The test is also a valuable index for cements which are to be used in making steam-cured concrete products.

* *Journal of Industrial and Engineering Chemistry*, Vol. 8, p. 1101.

† *Proc. A.S.T.M.*, Vol. 35, Pt. 2, p. 426.

‡ *Proc. Am. Conc. Inst.*, Vol. 34, 1937, p. 13.

TIME OF SETTING

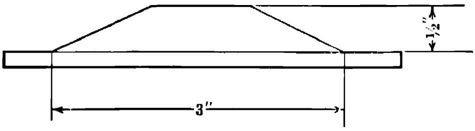
425. A.S.T.M. Method.—

36. The following are alternate methods, either of which may be used as specified:

Vicat Method.—37. The time of setting shall be determined with the Vicat apparatus described in Section 29. (See Fig. 4.)

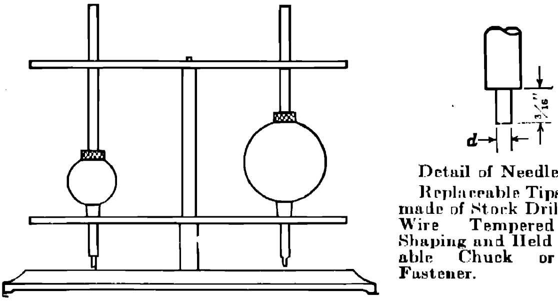
38. A paste of normal consistency shall be molded in the ring *G*, Fig. 4, as described in Section 30, and placed on the glass plate *H*. The needle *D* of the rod *B*, Fig. 4, shall then be lowered until it rests on top of a portion of the glass plate which projects beyond the ring *G*, and the adjustable indicator *F* set to the lower zero mark of the scale or an initial reading taken. The rod *B* shall then be raised, the needle *D* carefully brought in contact with the surface of the paste, and the rod quickly released. The initial set shall be said to have occurred when the needle ceases to pass a point 5 mm. above the glass plate in 30 seconds after being released; and the final set, when the needle does not sink visibly into the paste. The test pieces shall be kept in moist closet or moist room during the test. Care shall be taken to keep the needle clean, as the collection of cement on the sides of the needle retards the penetration, while cement on the point may increase the penetration. The time of setting is affected not only by the percentage and temperature of the water used and the amount of kneading the paste received, but also by the temperature and humidity of the air, and its determination is therefore only approximate.

Gillmore Method.—39. The time of setting shall be determined by the Gillmore needles. The Gillmore needles should preferably be mounted as shown in Fig. 8 (*b*).



(*a*) Pat with Top surface Flattened for Determining Time of Setting by Gillmore Method.

Note Cross Arms must be Designed to Prevent their Rotation about the Vertical Shaft.
Lower Arm Preferably Adjustable for Height.



Detail of Needle Tips.
Replaceable Tips may be made of Stock Drill Rod or Wire Tempered After Shaping and Held by Suitable Chuck or Other Fastener.

(*b*) Gillmore Needles.

FIG. 8.—Apparatus for Time of Setting Test.

The needle tips shall be cylindrical for a distance of about $\frac{3}{16}$ in. The needle ends shall be plane and at right angles to the axis of the rod and shall be maintained in a clean condition.

In addition to the above, the Gillmore needles shall conform to the following requirements:

INITIAL NEEDLE:		
Weight	$\frac{1}{4}$ lb. ± 8 grains	(113.4 g. ± 0.5 g.)
Diameter	$\frac{1}{12}$ in. ± 0.002 in.	(2.12 mm. ± 0.05 mm.)
FINAL NEEDLE:		
Weight	1 lb. ± 8 grains	(453.6 g. ± 0.5 g.)
Diameter	$\frac{1}{24}$ in. ± 0.002 in.	(1.06 mm. ± 0.05 mm.)

40. A pat from cement paste of normal consistency about 3 in. in diameter, $\frac{1}{2}$ in. in thickness at the center with a flat top and tapering to a thin edge, Fig. 8 (a), shall be made on a flat, clean glass plate about 4 in. square. In molding the pat the cement paste shall first be flattened on the glass and the pat then formed by drawing the trowel from the outer edge toward the center, then flattening the top. The pat shall be kept in moist closet or moist room at a temperature of 21° C. ± 1.7° C. (70° F. ± 3° F.) and a relative humidity of at least 90 per cent. The cement shall be considered to have acquired its initial set when the pat will bear, without appreciable indentation, the Gillmore needle $\frac{1}{12}$ in. in diameter, loaded to weigh $\frac{1}{4}$ lb. The final set has been acquired when the pat will bear, without appreciable indentation, the Gillmore needle $\frac{1}{24}$ in. in diameter, loaded to weigh 1 lb. In making the test, the needles shall be held in a vertical position and applied lightly to the surface of the pat.

426. Suggested Precautions.—Too great emphasis cannot be laid upon the latter part of Section 38. If reliable results are to be obtained the specimens should be made in a room at approximately 70° F. The water used in mixing and the moist closet in which test-pieces should be cured ought also to be kept at the same temperature.

In using the Vicat apparatus, trial tests on time of initial set should be made near the circumference of the ring leaving the center portion unmarked for the final test. The needle should never be allowed to strike forcibly upon the plate *H*. In testing with either device, final set may be considered to have occurred when the needle fails to register a circular indentation.

427. Comparison of Vicat and Gillmore Methods.—It will be appreciated that the determinations afforded by either of the above methods are purely empirical and that there is no reason why the results obtained by one method should agree with those gotten by the other. The only conclusion which can be stated is that either time of set determined by the Vicat apparatus is less than that gotten from the Gillmore needles. The discrepancy may range from a few minutes to over an hour. In a series of tests involving 594 specimens, six cements and thirty-four laboratories (see *Rept. of Joint Conference on Uniform Methods and Standard Specifications for Cement* (April 28, 1915)), the discrepancies averaged about 20 per cent for either initial or final set.* A comparison of these methods made in 1930 is shown in Art. 352.

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* For devices invented to record automatically the setting of cement, see *Engr. News* Vol. 46, p. 95 and Vol. 97, p. 66; *Cement Age*, Vol. 13, p. 138, and Vol. 14, p. 88.

Tensile Strength Tests

428. A.S.T.M. Method.—

Test Specimen.—41. The form of test specimen shown in Fig. 9 shall be used. The molds shall be made of non-corroding metal and have sufficient material in the sides to prevent spreading during molding. Gang molds when used shall be of the type shown in Fig. 10. Molds shall be oiled with a mineral oil. The dimensions of the briquet molds shall conform to the following requirements: width of mold, between inside faces, at waist line of briquet, 1 in. with tolerances of ±0.01 in. for old molds and ±0.005 in. for new molds; thickness of new molds, measured at point of greatest thickness on either side of mold at waist line, 1 in. with tolerances of +0.004 in. and −0.002 in.

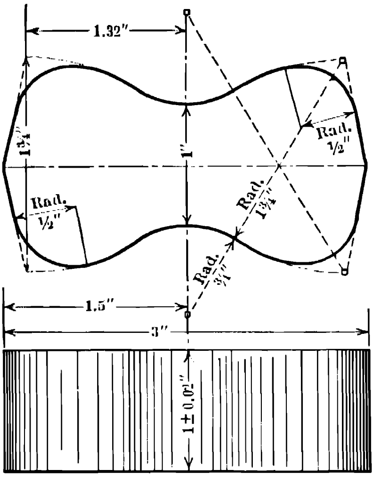

Fig. 9.—Details for Briquet.

Standard Sand.—42. The sand to be used shall be natural sand from Ottawa, Ill., screened to pass a No. 20 sieve and retained on a No. 30 sieve. This sand may be obtained from the Ottawa Silica Co., Ottawa, Ill.

43. This sand shall be considered standard when not more than 15 g. are retained on the No. 20 sieve, and not more than 5 g. pass the No. 30 sieve, after 5 minutes continuous sieving of a 100-g. sample, in the manner specified for sieving cement on the No. 200 sieve (see Section 22).

44. The No. 20 and 30 sieves shall conform to the requirements for these sieves as given in the Tentative Specifications for Sieves for Testing Purposes (A.S.T.M. Designation: E 11) of the American Society for Testing Materials.*

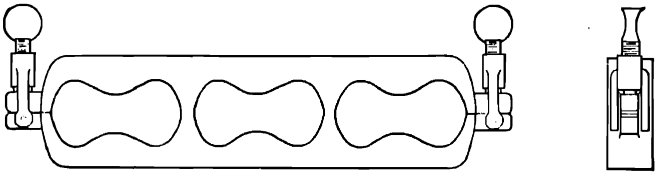

Fig. 10.—Briquet Gang Mold.

Molding Specimens.—45. The standard mortar shall be mixed in accordance with the methods for mixing cement pastes and mortars as described in Sections 25 to 28. Immediately after mixing, the molds, resting on unoiled glass or metal plates, shall be filled heaping full without compacting. Then the mortar shall be pressed in firmly with the thumbs, applying pressure 12 times to each briquet, at points to include the entire surface. The pressure shall be such that the simultaneous application of both thumbs will register a pressure of between 15 and 20 lb. Each application of the thumbs shall be maintained not longer than sufficient to attain the specified pressure. Then the mortar shall be heaped above the mold and smoothed off with a trowel. The trowel shall be drawn over the mold in such a manner as to exert a pressure of not more than 4 lb. The mold shall then be turned over upon a plane plate oiled with mineral oil, and the operation of heaping, thumbing, heaping and smoothing off repeated. No ramming or tamping shall be used, nor any troweling in excess of that required to smooth off the specimen. The thickness of the hardened briquet at the waist line upon removal from mold shall be 1 in. ±0.02 in.

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* 1936 Book of A.S.T.M. *Standards*, Part 2, p. 1413.

Storage of Test Specimens.—46. All test specimens, immediately after molding, shall be kept in the molds on plane plates in the moist closet or moist room for from 20 to 24 hours in such manner that the upper surfaces shall be exposed to the moist air, but protected from dripping water.

47. The moist closet or moist room shall be so constructed as to provide storage facilities for test specimens at a relative humidity of not less than 90 per cent and at a temperature of 21° C. ±1.7° C. (70° F. ±3° F.).

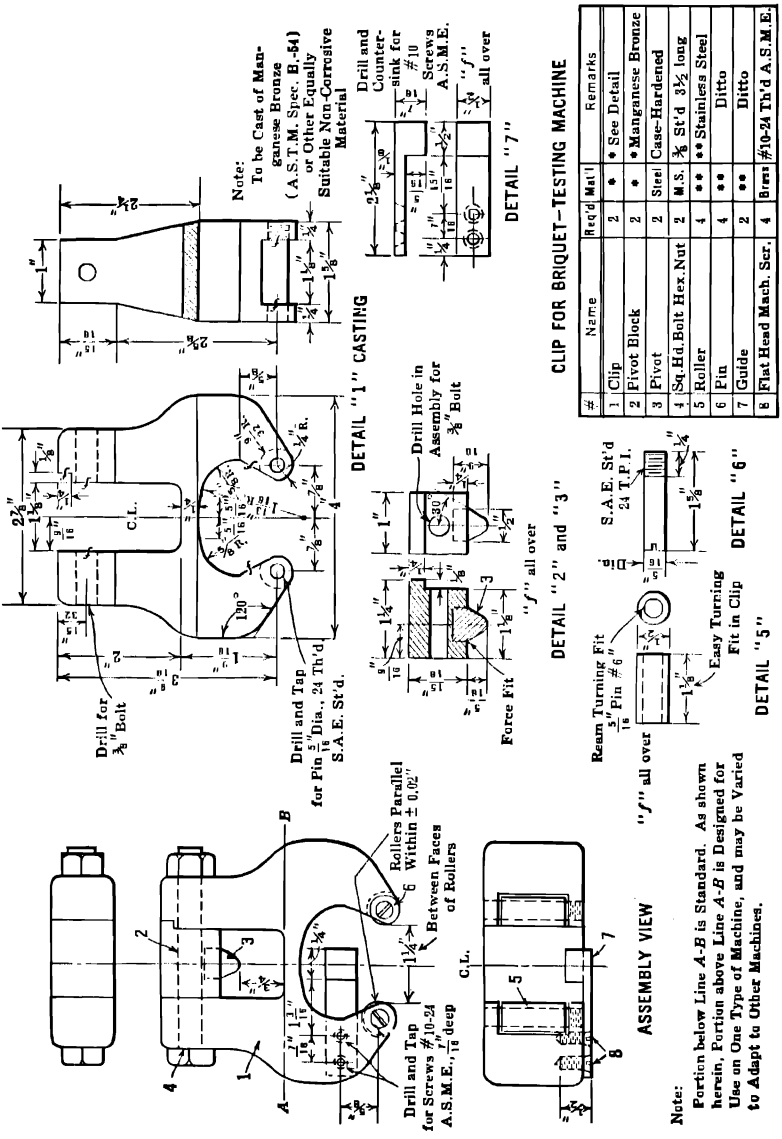
48. The briquets shall then be removed from the molds and immersed in clean water in storage tanks constructed of non-corroding material. The storage water shall be kept clean by frequent changing. If briquets should be removed from molds before 24 hours, they should be replaced on shelves of moist closet until expiration of the 24-hour period.

Tensile Strength Test.—49. The briquets shall be tested as soon as they are removed from the water. Tests may be made with any machine meeting the following requirements: The error for loads of not less than 100 lb. shall not exceed ±1.0 per cent for new machines or ±1.5 per cent for used machines. The clips for holding the tension test specimens shall be in accordance with Fig. 11. The bearing surfaces of the clips and briquets shall be free from sand or dirt, and the roller bearings shall be well oiled and maintained so as to insure freedom of turning. The briquets shall be carefully centered in the clips and the load applied continuously at the rate of 600 lb. ±25 lb. per minute.

50. Testing machines shall be frequently calibrated in order to determine their accuracy.

Faulty Briquets.—51. Briquets that are manifestly faulty, or which give strengths differing more than 15 per cent from the average value of all test specimens made from the same sample and tested at the same period, shall not be considered in determining the tensile strength.

429. Reasons for the Tension Test.—Although little reliance is placed upon the low tensile strength of concrete in making structural designs, the majority of strength tests on cements are tensile. This anomalous condition is due chiefly to three causes: first, the tensile strength is supposed to be a measure of the compressive strength; second, the tensile strength affords quicker indications of defects in the cement than other strength tests; third, this test is more conveniently made than the compression test since the small specimens used may be tested on an inexpensive machine of small capacity. The first of the above arguments is decidedly fallacious, since the ratio of the strength in tension to the strength in compression varies considerably with the strength of the mortar or concrete and to some extent with the type of cement. It may also be argued with considerable force that the form of test-piece, methods of mixing and molding, and the method of gripping are of such nature that compression tests of cubes can be made with as little variation as tensile tests on briquets. Figure 12 shows average ratios of compressive strengths of concrete made with a


Note: To be Cast of Manganese Bronze (A.S.T.M. Spec. B.-54) or Other Equally Suitable Non-Corrosive Material
DETAIL "1" CASTING
Drill and Counter-sink for #10 Screws A.S.M.E.
"f" all over
DETAIL "7"
Drill Hole in Assembly for 3/8" Bolt
Force Fit
"f" all over
DETAIL "2" and "3"
S.A.E. St'd 24 T.P.I.
DETAIL "6"
Ream Turning Fit 5/16" Pin #6
Easy Turning Fit in Clip
DETAIL "5"
"f" all over
Drill for 3/8" Bolt
Drill and Tap for Pin 5/16" Dia., 24 Th'd S.A.E. St'd.
Rollers Parallel Within ± 0.02"
Between Faces of Rollers
C.L.
Drill and Tap for Screws #10-24 A.S.M.E., 7/16" deep
ASSEMBLY VIEW
A
B
Note: Portion below Line A-B is Standard. As shown herein, Portion above Line A-B is Designed for Use on One Type of Machine, and may be Varied to Adapt to Other Machines.
CLIP FOR BRIQUET-TESTING MACHINE

#	Name	Req'd	Mat'l	Remarks
1	Clip	2	*	* See Detail
2	Pivot Block	2	*	* Manganese Bronze
3	Pivot	2	Steel	Case-Hardened
4	Sq.Hd.Bolt Hex.Nut	2	M.S.	3/8 St'd 3½ long
5	Roller	4	**	** Stainless Steel
6	Pin	4	**	Ditto
7	Guide	2	**	Ditto
8	Flat Head Mach. Scr.	4	Brass	#10-24 Th'd A.S.M.E.

FIG. 11.—Clip for Briquet-Testing Machine.

water-cement ratio of 1, by volume, to the tensile and to the compressive strengths of 1 : 3 mortars of standard Ottawa sand. (From the 1934 report of Com. C 1 of the A.S.T.M.) It will be noted that the ratios of the compressive strengths are much more nearly constant. Further data on the comparative reliability of mortar tension and compression tests was reported by Com. C1 in 1938.

The data presented by the Project Committee on Cements of the Highway Research Board (see *Proc.*, 1936), show that 2 by 2 by 10-in. prisms can be made to yield reliable indices of both the flexural and compressive strengths of cements. Since the flexural strength is directly related to the tensile strength, this test appears ideally fitted to give information both with regard to tensile and compressive strengths when the supply of material for testing is small.

In specifications for Portland cement it seems desirable to include both tension and compression requirements on 1 : 3 mortars of standard consistency as has been the practice in many foreign countries.*

430. Indications Afforded by Neat and Mortar Tension Tests.—Neat cement paste, though unstable under atmospheric conditions, is occasionally tested in tension after 12 to 24 hr. to ascertain the rate of hardening.

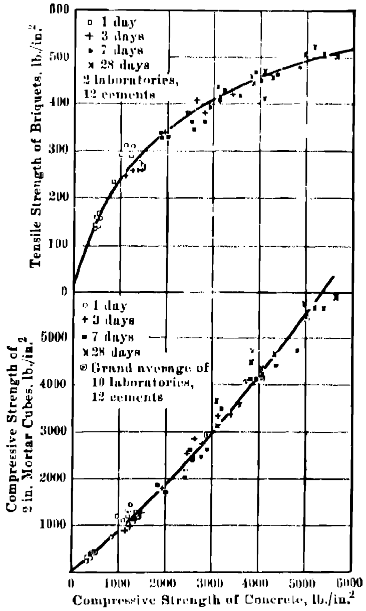


FIG. 12.—Relation of Strengths of Standard Ottawa Sand Mortars to Compressive Strength of Concrete. (Rept. Com. C1, A.S.T.M., 1934.)

Tension tests of mortars must be considered as rather sensitive indices of quality *provided standard conditions are maintained.* As measures of the compressive strength of concrete they are only rough criteria.

When the time allowed for testing is short, tests on 1 : 3 mortar briquets of standard sand give valuable indications of quality. Such briquets should exhibit a strength of 210 lb. per sq. in. at 3 days. Care must be taken, however, to maintain moist closet and water bath at 70° F., since tests at the University of Wisconsin have shown that the strength of 3-day mortar briquets may be decreased 20 lb. and that of 7-day briquets 10 lb. by immersion in water at 60° F.

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* Now a standard. See A.S.T.M., Des. C109–44, and C150–46.

431. The Theory of the Distribution of Stress over the Minimum Section of a Cement Briquet has been developed by M. Durand-Claye in *Annales des Ponts et Chaussées,* June, 1895. He found for the form of briquet shown in Fig. 9 that the ratio of the maximum to the minimum unit stress was 2.12 to 1 and the ratio of the maximum to the average unit stress was 1.54 to 1. Prof. Coker in *Proc. I.A.T.M.*, 6th Congress, 1912, gave proof based on experiment that the latter ratio was 1.7 to 1. These investigations show that the intensity of stress is greatest along the sides of the minimum section and least at the center.

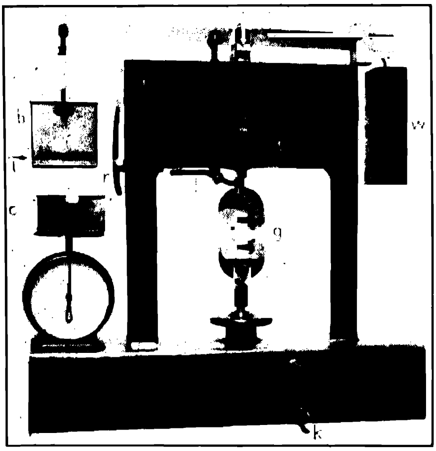

FIG. 13.—An Olsen Automatic Shot Briquet Tester.

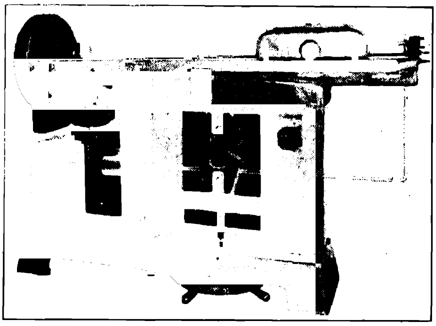

FIG. 14.—A Riehle Motor-Driven Automatic Briquet Tester.

432. Precautions to Observe in Molding Briquets.—The operator should note well that Section 45 of the Specifications prohibits the use of rammers in filling the molds. When such devices are used, or when the molds are filled in thin layers, the early strength of the specimens will be greater than if made in the standard manner. Care should also be taken to see that the minimum cross-section of the briquet is exactly 1 in. thick. Briquets varying in thickness from the above dimension will be eccentrically loaded when tested in standard grips; and, as a result, their load-carrying capacity will be decreased. To assist in estimating the correct pressure in molding, inexperienced operators should practice molding on platform scales or on delimeters.

433. Types of Testing Machines.—A very efficient and simple device for testing the strength of briquets is shown in Fig. 13. In starting the test, sufficient fine shot is placed in the bucket, *b*, to counterbalance the weight, *w*. After the briquet is adjusted in the grips or clamps, *g*, the trigger, *t*, at the bottom of the bucket is released; this opens a valve which allows shot to flow down into the cup, *c*. As the shot flows from the bucket the weight, *w*, moves downward; and, through the lever system, a stress is produced upon the briquet which is proportional to the shot lost. To keep the beam in the central position, the crank, *k*, is turned in the clockwise direction. When the briquet breaks, the lever, *l*, is tripped, releasing the spring in trip-lever, *r*; thus the valve is immediately closed and the flow of shot stopped. The spring balance is graduated to read the load on the briquet to the nearest 5 pounds.

Figure 14 shows a precision automatic briquet tester in which the load is applied to the specimen by a poise traveling along the single loading lever. The rate of loading is positive and constant. Poise stops instantaneously with the fracture of the test piece, and the load is read directly from the loading lever.

434. The Effect of Eccentric Loading on the Strength of Briquets.—In making briquet tests it is of great importance that the load shall be centrally applied. To avoid errors from such eccentric loading, the roller and pivot alignment of new sets of grips should be carefully checked to see that the load line coincides with the axis of the specimen. Similar checks should be periodically made on grips subject to severe usage. Furthermore, the operator should see that any projecting edges are removed from the specimens, that the rollers work freely and have a bearing over the entire width of the briquet, and that the specimen rests against the bars on the back of the clips. Tests made at the Massachusetts Institute of Technology * show that a displacement of $\frac{1}{16}$ in. will decrease the strength from 15 to 20 per cent.

Since briquets become more brittle with age, the effect of a slight eccentricity or any torsional strain will be more marked in long-time tests than in those made at an early age.

435. The Effect of the Rate of Loading on the Strength of Briquets.—A number of series of experiments have been made to determine the effect of rate of loading on the tensile strength of briquets. These show that the strength increases with the rapidity of loading. Since variations of 100 lb. per min. in the rate of loading may cause changes of 2 per cent in the observed strength,† the operator should frequently check his machine to see that the speed of loading conforms to requirements.

436. Number of Specimens.—It is good practice to break from three to five briquets at each period. If the work is carefully done an individual result should not vary more than 10 per cent from the mean.

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* *Trans. Am. Soc. Mech. Engr.*, Vol. 9, p. 181.

† See experiments by W. P. Taylor in his *Practical Cement Testing*, p. 148; also Wheeler's tests, *Report of Chief Engrs.*, U. S. A., 1895, p. 2951.

437. Calibration and Standardization of Equipment.—The National Bureau of Standards maintains a Cement Reference Laboratory which, upon request, will furnish instruction with regard to standard methods of making tests and proper procedure in care and calibration of equipment. The Bureau's *Circular* No. 9 gives requirements for graduates and burettes; *Handbook M 85* covers calibration of balances and weights. Periodically the weights, diameters of needles, and conditions of the ends of needles on Vicat and Gillmore Needles should be checked. Briquet molds should be checked to see that they are properly mated and the thickness and width at the minimum section should be measured. Briquet-testing machines should be tested for accuracy and sensitivity and, if necessary, the knife edges should be sharpened. Roller bearings on grips and rate of flow of shot should be checked daily for freedom of revolution and at least once a month for alignment.

438. Moist Closet.—The temperature in the moist closet should be kept at 70° F. ± 5° F. A suitable form of closet is that shown in Fig. 15; one made of concrete is described by E. B. McCready in the *Engr. News*, Vol. 58, p. 107; an elaborate closet, designed for constant temperature, is described by W. F. Purrington in *Concrete*, Oct., 1927, p. 47.

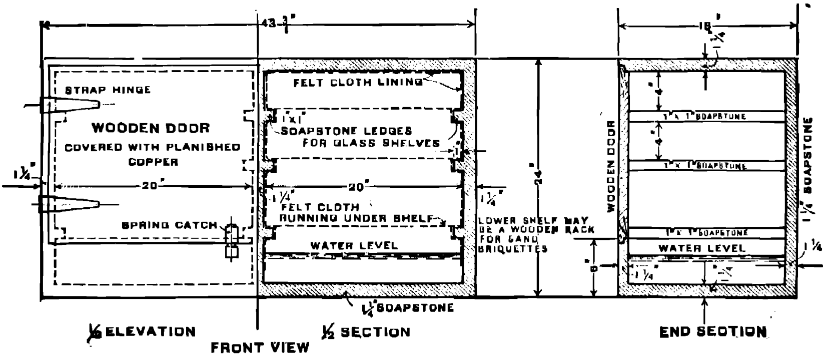

Fig. 15.—Moist Closet. (From *Concrete, Plain and Reinforced;* by Taylor and Thompson.)

439. Storage Bath.—After specimens are removed from the moist closet they should be stamped or marked with a lead pencil or waterproof crayon before immersion in the water bath. Briquets should be marked near the ends. The bath should be supplied with pure running water or the water in the tank should be changed daily. If this is not done, the salts liberated in curing form solutions which affect the strength of the specimens. A convenient water bath is shown in Fig. 16.

For the effect on strength of early removal of specimens from storage bath see Fig. 12, Ch. IX.

THE INTERPRETATION OF THE RESULTS OF STANDARD TESTS

440. General Recommendations.—The student should always bear in mind that the tests are only of qualitative value for the purpose of comparing the sample with a standard, adopted after long experience, or to compare it with previous samples of the same brand of cement. Therefore, before accepting or rejecting a cement, he should carefully consider the relative value of the results of each test and the conditions under which the cement is to be used. Furthermore, one should not condemn a sample unless certain that the conditions surrounding each test were standard. Any uncertainty in regard to a result should be removed by performing a second test under standard conditions. Below will be found a brief discussion of the criteria determining the acceptability of Portland cement arranged in order of the importance of the various tests.

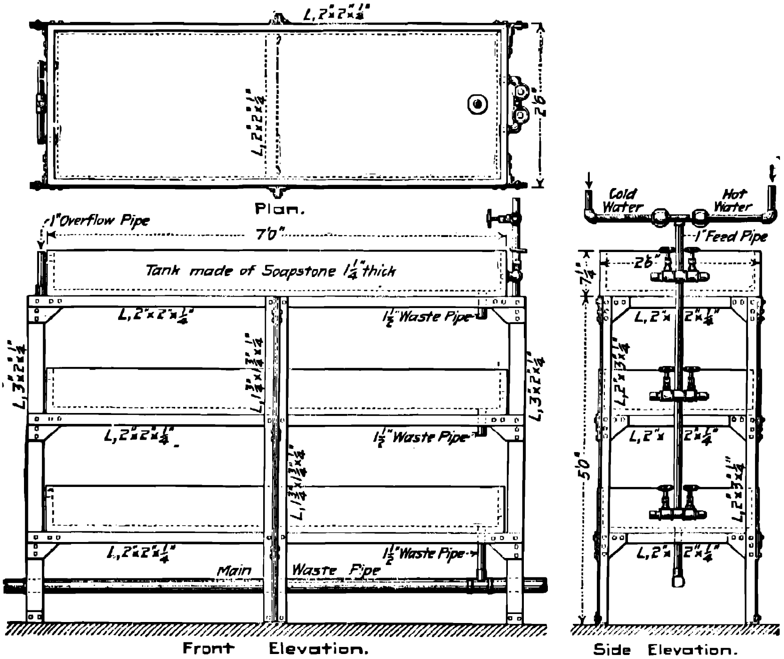

FIG. 16.—Sketch of Storage Tanks for Briquets. (From Taylor's *Practical Cement Testing*.)

441. Soundness.—If one or more steamed pats show signs of distortion, checking, disintegration or radial cracks (Fig. 6) the cement should be rejected; or if conditions permit the cement may be stored and further soundness tests made.

Although the accelerated soundness test is made under abnormal conditions, yet the results of a thousand boiling tests made by W. P. Taylor on different brands of cement bear witness to its value. He found that about one-third of the cements failing in the boiling test gave evidence of unsoundness in air-cured pats or a retrogression in strength inside of twenty-eight days; within one year approximately seven-eighths of these cements had given like evidence of unfitness. Furthermore, only one-half of 1 per cent of the cements which passed the boiling test showed signs of unsoundness in the air pat tests and only 13 per cent retrograded in strength within the year.

442. Tensile Strength.—Reject the cement if the strength at twenty-eight days is less than required by the specifications. If the strength of the mortar briquets at twenty-eight days is less than at seven days, reject. If the strength of mortar briquets is a trifle below the standard at seven days but is above at twenty-eight days, accept the cement. If judgment must be passed upon a sample at the end of seven days, reject on a decidedly low mortar test. Hold for twenty-eight days if the mortar strength is slightly below the standard.

443. Time of Set.—If the cement does not pass the specification in the laboratory test, determine its behavior under conditions in which it will be used before condemning it. Slow final set may be due to coarseness, which will also affect the tensile strength of the mortar briquets.

444. Fineness.—Inasmuch as no sieves made at the present time are sufficiently fine to determine the percentage of flour, the important cementing element, this test has only corroborative value. Generally, a coarse cement will exhibit a low mortar strength and will oftentimes fail in the soundness test. Surface area measurements by turbidimeter are more informative than the results of sieve tests.

For further information on interpretation of results of cement tests, consult W. P. Taylor's *Practical Cement Testing* or R. K. Meade's *Portland Cement.*

MISCELLANEOUS TESTS OF CEMENTS AND MORTARS

445. Tests on Cement for Research Purposes.—Cement for research purposes should be tested in strict accordance with the standard specifications. In order to obtain representative results and to eliminate personal equation and variable laboratory conditions, it is desirable to make at least five specimens for each variable of the test. Such specimens should be made on different days so that each final average of five or more specimens will represent as many different batches.

For ascertaining the concrete-making properties of cements, tests made on concrete according to the Standard Methods of Making Compression

Tests of Concrete (A.S.T.M. Standards C 39–33, see App. A) are more effective than briquet tests.

446. Preparation of Materials for Mortar Tests.—Mortar tests are usually made to determine the quality of the mortar or the suitability of fine aggregate for making mortar or concrete. The Portland cement used in such tests should conform to standard specifications, unless it is one of the variables of the test.

In determining the quality of a mortar, the aggregate should be screened to a size suitable for the specific purpose for which it is intended. In determining the concrete-making qualities of a fine aggregate, the aggregate should be passed through a No. 4 sieve or a ¼-inch screen.

Aggregate should preferably be air-dry. When sands are to be used on the job without drying, they should also be tested with their natural moisture content. The quantity of water they contain may be determined on separate samples and the weights of sand and water used in the tests determined accordingly.

447. Determination of Normal Consistency in Mortar Tests.—A small flow table having a top diameter of 10 in. is a satisfactory device for measuring the relative consistency of mortars. A conical frustum having a top diameter 2.75 in., bottom diameter 4 in., and altitude 2 in. is placed in the middle of the table. After the mortar has been mixed in the standard manner (Art. 414), it is placed in the frustum in two layers. Each layer is rodded fifteen times with a ⅜-in. rod and the mold is removed. By means of a cam, the table is then raised ½ in. and dropped 25 times in 15 seconds. The index of consistency, the flow, is determined by calculating the ratio of the diameter of the mass after vibrating to the original base diameter of the frustum and expressing the ratio as a percentage.

In mortar tests on the structural strength of fine aggregate, standard consistency obtains when the mortar exhibits a flow of 100±5 after being subjected to 30 ⅛-in. drops in 30 seconds.

448. Compression Tests of Mortars.—A 2-by-4-in. cylinder of cold drawn brass tubing split along one element makes a satisfactory mold for mortar compression specimens. Two-inch cubes may also be used for mortar tests. Although cylinders have the advantage mentioned in Art. 113, they require capping. On the other hand cubes made in true molds may be tested by loading side faces. Since average unit strengths of 2-in. mortar cubes and cylinders are practically the same, the smaller cube specimen is favored by many for such tests. Approximately 500 grams of cement and sand are required for one cylinder and 320 grams for a cube. Standard procedure, Art. 414, should be used for mixing. Mortar should be placed in cubes in 2 equal layers, in cylinders in 3 layers. Each layer should be rodded 25 times with a ⅜-in. rod. After 3 or 4 hours tops of specimens should be struck off to a smooth surface. Specimens should be cured in molds in moist closet for the first 24 hours and thereafter in water.

Cylinders must be capped with plaster of Paris or equally suitable material prior to testing, without permitting them to dry. An oiled glass plate should be forced down on the capping to produce an even surface.

In testing, 3 to 5 specimens should be broken at each test period, using a spherical bearing block. The speed of the movable head for loads in the vicinity of the maximum should not exceed 0.03 in per min.

449. Transverse Tests.—Although transverse bending tests of cement mortars have been used to some extent, they have not been a specification requirement. Such tests can be made with less expensive molding and testing equipment than required for either the tension or compression test. When properly made they furnish as concordant results as either of the latter.

M. Durand-Claye has shown by very extended series of tests in tension and in cross-bending, on identical samples of neat Portland cement, that the average ratio of the modulus of rupture in cross-bending to the tensile strength, as determined upon standard forms of briquets, is 1.92 at seven days and 1.86 for twenty-eight days, or an average of 1.89. This relation was found to subsist between averages made up from the means of the three tests in each set of six, in both tension and cross-bending. The mean error of a single test at twenty-eight days was found to be 2.10 per cent for the tension tests and 2.13 per cent for the tests in cross-bending, thus showing that the two methods of testing were equally accordant.

For mortars of aggregates under ¼-in. in size, a prism 1 by 1 by 6 in. tested under center load over a 5-in. span makes a satisfactory specimen. Gang molds of non-corrodible metal holding five such prisms can be made very cheaply. Twelve hundred grams of dry material is ample for making five such specimens.

At least three, and preferably five, specimens should be broken at each test period. The automatic shot briquet testing machine (Fig. 13) can be provided with an auxiliary breaking attachment for these prisms in the space between the frame and shot bucket (*b*).

By inserting non-corrodible plugs in the ends of the cross-bending prisms, they can also be used for expansion measurements, although a longer prism is preferable.

450. Methods of Testing the Adhesion of Cement and Cement Mortars to Various Substances.—While the tensile strength of briquets shows the cohesion of the mortar, it has been found by experiment that its adhesion either to other mortars or to the same mixture which has already hardened, or to brick or stone or metal, is very much less than its cohesion. It is important, therefore, to have a standard test of adhesion, as well as of strength. Because tests of this kind are comparatively new, no general custom has been established in America on the subject; but the following recommendations have been made by the French Commission:

(1) For tests of adhesion of cements and cement-mortars use will be made of a special form of briquet, molded in two parts, these two parts consisting of the two materials whose adhesion is to be tested, provided both can be molded, or containing between them a prism of the solid body to which the adhesion of the mortar is to be determined. The form of this briquet, as modified for English units, with 1 sq. in. of area on the surface of adhesion, is shown in Fig. 17. This mold is formed in two parts, and is used to form in succession the two halves of the complete briquet.

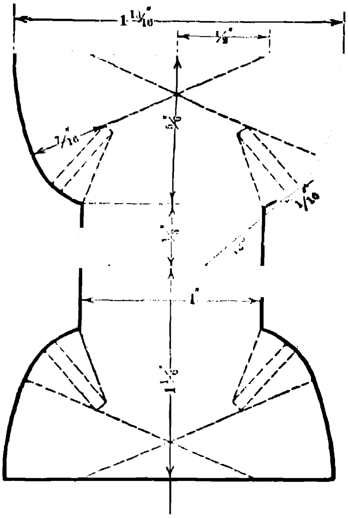

FIG. 17.—Form of Briquet for Adhesion Test of Cement as Adopted by the French Commission and Adapted to English Units.

(2) *To compare the force of adhesion of different cements to a given material, normal adhesion-blocks* will be prepared as follows: Use for these always one kind of standard Portland cement which has passed a sieve of eighty meshes to the linear inch, mixed with the standard sand No. 3 (sand passing a No. 15 and held on a No. 11 sieve) in the proportion of one of cement to two of sand. These normal adhesion-blocks will be molded in the form of one half of the briquet shown in Fig. 17.* It will be gaged with 9 per cent of water and rammed into the mold. At the end of twenty-four hours in air it will be placed in fresh water for a period of at least twenty-eight days. When it is to be used, it will first be dried and its adhesion-surface polished with emery-paper.

(3) The cement to be tested for adhesion with these standard blocks prepared as above will be mixed as a normal plastic mortar, one of cement to three of sand (the consistency advocated is about the same as the A. S. T. M. recommends), which will be introduced into the mold with a trowel, this mold now being placed with a normal adhesion-block at the bottom in place of the movable metallic disc. The mold will remain upon this completed block until it is ready for testing, and the block will be allowed to harden either in air or water, and for such period as the test

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* The detail drawings of these molds are given in *Com. des Méthodes D'Essai Mat. Const.*, Vol. 4, p. 284.

requires. It is recommended that the number of tests, the periods of time, the methods of hardening, and the recording of the results should comply with the conditions given for tension tests of cement.

(4) *To compare the force of adhesion of a given cement to different materials:* For this purpose the test-specimens will be prepared as described above, except that in place of the normal adhesion-blocks similar blocks of the various materials to be tested will be prepared and allowed to harden, provided these are such as can be molded in this manner. If such materials are solid, small discs, about $\frac{3}{8}$ in. thick, will be prepared, and these will be used in the bottom of the mold in place of the metallic disc, the adhesion-block to be completed by using neat Portland-cement mortar. After this has hardened the briquet will be completed by making the other half of a standard plastic mortar, one cement to three of sand, using the particular kind of cement whose adhesion to these various substances is to be tested.

If the normal plastic mortar is not used in adhesion tests, a full description of its composition should be indicated on the records.

These adhesion-briquets should be broken on a standard tension-testing machine, using the regular tension-clips.*

In connection with the methods of testing adhesion, one should also examine the report of Feret on "The Adhesive Strength of Hydraulic Cements," *Proc. I.A.T.M.*, Brussels Congress, 1906, Problem 10. As the result of a number of experiments Feret advocates the use of a prismatic specimen 4 by 4 by 16 cm. (1.6 by 1.6 by 6.4 in.) in dimensions, one end of which is bonded to the body with which adhesion is to be tested. He outlines very careful methods for mixing, molding, and curing the specimens and recommends that the prisms be torn apart by subjecting them to a uniform bending moment.

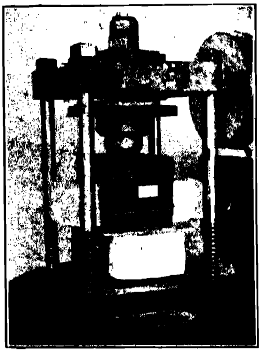

FIG. 18.—Method of Testing Tension Bond of a Mortar Joint.

A considerably used arrangement for determining the bond of mortar to brick is shown in Fig. 18. The area bounded on one brick is 12 to 15 sq. in. For successful use at least 5 specimens per point should be made, and uniformity must be maintained in conditioning the brick, making the joints, curing, and in centering the apparatus on the specimens in testing.

451. Methods of Determining Yield.—This test is used primarily to determine the volume of paste, mortar or concrete which can be obtained from given proportions of the ingredients. It is also possible to determine the density of the mixture from the test, if the weights and specific gravities of each ingredient are known.

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* In order that the specimens may fit *A.S.T.M.* grips, a slight modification of the above form will be found necessary.

The French Commission recommended that the yield be determined in either of the following ways: The volume of 1 kg. of neat cement paste or mortar of proper consistency should be measured by compacting in a glass burette about $2\frac{5}{8}$ in. in diameter, due care being taken to expel any entrained air; or, the set paste may be weighed in air and in water and the yield computed from the loss in weight. See also Art. 463.

452. Methods of Testing the Permeability of Cements and Mortars.—The permeability of cement-mortar is often a very important matter, as in the case of reservoir wells and linings, and often in foundation walls placed below ground-water level.

Professor Tetmajer has used the apparatus shown in Fig. 19 to obtain a modulus of permeability. Here a cylinder of the mortar is made and allowed to harden under water for a specified time. It is then mounted in the apparatus by means of annular rubber-cushion or packing discs, and the water let on below under a known pressure. The permeability of the mortar is indicated by the rate at which the water passes the disc and rises in the glass tube above, which is graduated to cubic centimeters. Also see methods in Art. 524.

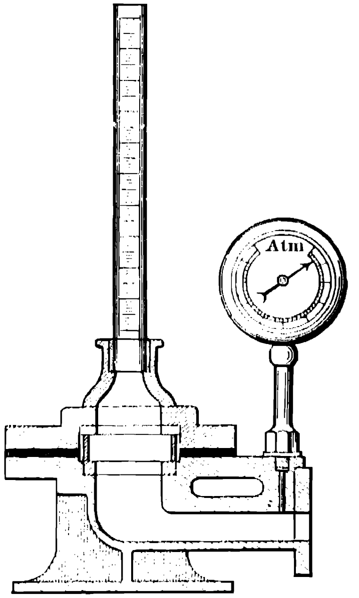

FIG. 19.—Tetmajer's Apparatus for Testing the Permeability of Cement-mortar. (Mitteilungen der Material-prüfungs-Anstalt, Poly. Zurich, Vol. 6.)

453. The Estimation of the Constituents in Mortars or Concretes.—Often a knowledge is desired concerning the proportions of cement and aggregate in a finished concrete structure. Rough determinations can be made by examining several representative samples under a microscope and estimating the proportion of the field covered by each constituent. A more accurate analytical method is given in *Bulletin* 61, Engineering Expt. Sta., Ames, Iowa. (Also see A.S.T.M., Des. C 85–36.)

In order to test the homogeneity of fresh concrete, to check variations of manufacture, and to establish better field control over mixes, analyses of fresh concrete can be made. This can be done by wet screening the constituents and measuring their absolute volumes by weighing them under water. An effective method for so doing is described by W. M. Dunagan in *Bulletin* 113, Engr. Expt. Sta., Ames, Iowa.

CHAPTER XIII

MAKING MORTAR AND CONCRETE

454. Introduction.—When using concrete and mortar in construction the engineer is placed in the position of a manufacturer who fabricates a finished structural product from several raw materials. It is, therefore, necessary that he should be thoroughly cognizant of the properties of the constituent materials and the methods of handling them in order that a satisfactory product will result. In view of this consideration and in view of the great number of concrete constructions now being built, we shall pay considerable attention to the important factors which enter into the making of mortar and concrete.

It will be appreciated that very often the ideal conditions hereinafter mentioned cannot be attained in practice: Old cement must sometimes be used; only a fine-grained sand is attainable; the gravel is dirty or is of decidedly variable gradation and cannot be economically screened; a very wet consistency must be used on account of difficulties encountered in placing the concrete; or no care can be given to providing suitable curing conditions. Very often such undesirable conditions may be offset, to a large extent, by increasing the proportion of cement in the mixture. Many times it will be found economical to use local material of poor quality in a rich mixture rather than to ship in a superior sand or gravel and use a lean mix. Then, too, there is often a wide variation in the finished concrete due to methods of handling.* Changes in consistency may easily produce variations of 100 per cent in strength and the methods of mixing and placing adopted by different concerns may also be responsible for as wide variations in properties. All of these facts emphasize the necessity of testing samples of concrete, made under the conditions of practice, before deciding upon the proper mixture to use; and also, they point out the importance of testing the product as used in the work.

Owing to the haste with which concrete structures are often built and the lack of facilities for testing, there has been a great reticence on the part of engineers to specify tests of concrete. They have framed specifications containing demands for certain more or less easily determined properties of the cement, sand, and broken stone; have called for certain proportions, and have stipulated a method of mixing; but definite specifications for the properties of the manufactured product are in most cases wanting.

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* See results obtained by U. S. Bureau of Standards in *Technologic Paper* No. 58

An undue reliance is placed upon the acceptance tests of the constituent materials. These tests are valuable and serve to eliminate most poor material. Nevertheless, the acceptance tests sometimes advocated for sands are not always true criteria of the relative values of the concretes made from them, and sometimes cause the rejection of satisfactory material. Bearing these facts in mind, we shall now consider the properties of aggregates and the methods of testing and proportioning them. In order to appreciate better the significance of certain much-used terms their definitions will receive first attention.

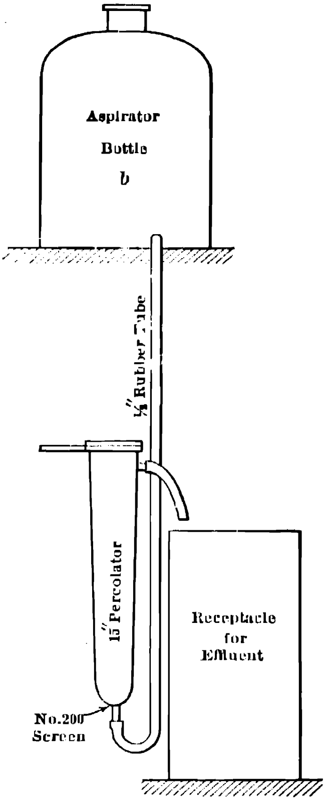

Fig. 1.—Apparatus for Determining Amount of Silt in Aggregate.

DEFINITIONS

455. Mortar.—A mixture of sand, screenings, or similar inert particles, with cement and water which has the capacity of hardening into a rocklike mass is called mortar. In general the maximum size of the inert particles in mortars is less than $\frac{1}{4}$ inch.

456. Concrete.—A mixture of crushed stone, gravel, or similar inert material with a mortar is called concrete. The maximum size of inert particles in concrete is variable but is ordinarily under two inches. Rubble concrete is made by embedding a considerable proportion of large boulders or blocks of stone in concrete.

457. Cement.—The binding agencies most commonly employed in making concrete are the hydraulic cements and the bitumens. In this book only concrete and mortar made from the hydraulic cements will be considered; and, whenever, in this and succeeding chapters, the term concrete or mortar appears unqualified, Portland cement should be understood to be the binder. For information concerning the properties, the methods of testing and the standards for cements, reference should be made to Ch. IX, X, XI and XII.

458. Aggregate.—The inert particles within concrete or mortar comprise the aggregate. Although no hard and fast division can be made sands, screenings, mine tailings, pulverized slag, etc., in which the maxmum diameter of particles is less than $\frac{1}{4}$ in. may be classed as fine aggregate; crushed stone, gravel, cinders, slag and the like containing larger particles are called coarse aggregate.

459. Silt is the impalpable dust which is present, at least in small proportion, in nearly all aggregates. The amount of silt can be determined with the apparatus shown in Fig. 1. One or two hundred grams of dry fine aggregate is carefully weighed, placed in the percolator and washed by a stream of pure water from the bottle (*b*). The silt is continuously stirred with a glass rod until the effluent from the percolator becomes clear. The residue in the percolator is then dried, and the loss in weight determined. If an analysis of the silt is desired the effluent from the percolator is filtered, and the residue on the filter is dried and analyzed. In order to obtain consistent results the dimensions of the percolator, velocity of flow of water, size of orifice and method of stirring should be standardized.

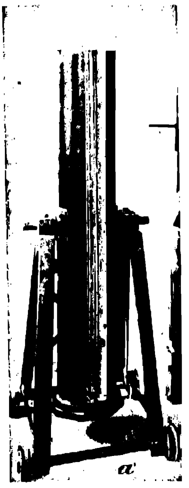

FIG. 2.—Voidmeter.

√ **460. Specific Weight.**—The weight of an aggregate contained in a measure of unit volume is called its specific weight. Generally the units of volume used in this country are the cubic foot and the cubic yard.

Inasmuch as this determination is affected by the moisture content of the aggregate due consideration of the latter should be given. In specific weight determinations on fine aggregate the results for dry material cannot be accurately computed from tests in which the moisture content is sufficient to wet the surfaces of the particles. (See Art. 171.) Obviously the degree of compactness of the material also greatly influences the specific weight; hence the adjectives rammed, compacted, shaken-down and loose are used. Loose measurement is often used in the field.

The method recommended in the A.S.T.M. specifications (Ser. Des. C 29-27) for determining the specific weight of aggregate consists of filling a cylindrical measure of $\frac{1}{10}$, $\frac{1}{2}$, or 1 cu. ft. capacity and determining the net weight of the aggregate in the measure. The sample of the aggregate shall be room dry if possible, and thoroughly mixed. The measure shall be filled one-third full, leveled off, and tamped twenty-five times with a $\frac{5}{8}$-in. pointed rod. The measure is filled two-thirds full and tamped twenty-five times as before. The measure shall then be filled to over-flowing, tamped twenty-five times, and the surplus aggregate struck off, using the rod as a straightedge. No effort should be made to fill holes left by the rod when the aggregate is damp. The size of measure to be used is determined by the size of aggregate, the $\frac{1}{10}$ cu. ft. to be used for aggregate whose particles are under $\frac{1}{2}$ in. The $\frac{1}{2}$- and 1-cu. ft. measures are for aggregates whose particles are under 1½ in. and over 1½ in., respectively. (See also Rept. of Com. C 9, *Proc. A.S.T.M.*, 1938.)

461. Voids.—If an aggregate is poured into a container of any sort it will be observed that not all of the space within the container is filled. To the vacant spaces between the particles of aggregate the name voids is applied. Necessarily, the percentage of voids like the specific weight is affected by the compactness of the aggregate and the amount of moisture which it contains. Generally void determinations are made on material measured loose.

There are two classes of methods commonly employed for measuring voids, the direct and the indirect. The most-used direct method consists in determining the volume of liquid, generally water, which is required to fill the voids in a given quantity of material. Since in pouring water into fine aggregate it is impossible to expel all the air between the particles, the measured voids are smaller than the actual. It, therefore, becomes evident that the above direct method should not be used with fine aggregates unless the test is conducted in a vacuum. By the indirect method the solid volume of a known quantity of aggregate is gotten by pouring the material into a calibrated tank partially filled with water; the difference between the apparent volume of material and the volume of water displaced equals the voids. If very accurate results are desired void measurements should be corrected for the porosity * of the aggregate and the moisture it contains. If the latter corrections are made the specific gravity may also be gotten by this method (see Art. 409). Fig. 2 shows a convenient device for measuring voids by this indirect method.†

When the specific gravity of the aggregate is known the voids may be calculated thus:

$$\text{Per cent voids} = \frac{62.5 \times \text{sp. gr. of aggregate} - \text{wt. per cu. ft. of aggregate}}{0.625 \times \text{sp. gr. of aggregate}}.$$

The variation in the size of particles in the aggregate greatly affects the voids. If a mass of spheres of equal diameters be piled as compactly as possible it may be shown that the per cent voids is approximately 26.‡ If spheres of smaller diameter, which will just fit into interstices in the original pile, are added, it is evident that the voids may be reduced. By the insertion of a third lot of still smaller spheres within the voids left in the pile a further reduction in voids may be made. Although particles of aggregate cannot be assigned to such definite positions, especially if they are loosely piled, yet experiments have shown that the voids in loose material may be greatly decreased by properly grading the sizes of the constituent particles.

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* See Art. 269.

† For other devices for determining voids see *Bulletin* No. 329, U. S. G. S.

‡ See *Concrete Plain and Reinforced*, by Taylor and Thompson, 3rd Ed., p. 130, for demonstration.

462. Mechanical analysis consists in determining the proportionate amounts of particles held on or passing through a series of sieves differing in size of mesh. Such analyses indicate whether the material is properly graded to produce the minimum voids, when it is made into mortar or concrete. They also provide a means of studying how the gradation of particles may be improved by making proper additions and how different grades of aggregates may be combined with cement to form the most efficient mix.

For analyzing fine aggregate it is common practice in this country to employ sieves made of woven-brass wire. In some laboratories sheet brass perforated with circular holes is used instead of the wire cloth. The number of meshes per linear inch, the diameter of wire and size of opening of the more commonly used sieves of the United States Standard Sieve Series are given in Table 1. The sieves marked * and listed in the lower part of the table are sufficient for most gradation tests on fine aggregates. Sieves for fine aggregate are generally made 8 in. in diameter and 2¼ in. deep. They are so fashioned that they may be nested one above the other with the sizes arranged in order of fineness of mesh from the bottom upwards.

TABLE 1.—REQUIREMENTS FOR SIEVES FOR TESTING CONCRETE AGGREGATE

Standard Sieve Series Number	Sieve Opening		Wire Diameter		Tolerance in Average Opening Per Cent	Tolerance on Wire Diameter, Per Cent		Tolerance in Maximum Opening, Per Cent
	mm.	in.	mm.	in.		Under	Over	
3-in.*	76.0	3.00	6.3	0.25	±3	10	10	10
2-in.	50.8	2.00	4.88	0.192	±3	10	10	10
1½-in.*	38.0	1.50	4.50	0.177	±3	10	10	10
1-in.	25.4	1.00	4.12	0.162	±3	10	10	10
¾-in.*	19.0	0.75	3.42	0.135	±3	10	10	10
⅜-in.*	9.5	0.375	2.33	0.092	±3	10	10	10
4*	4.76	0.187	1.27	0.050	±3	15	30	10
8*	2.38	0.0937	0.84	0.0331	±3	15	30	10
10	2.00	0.0787	0.76	0.0299	±3	15	30	10
12	1.68	0.0661	0.69	0.0272	±3	15	30	10
16*	1.19	0.0469	0.54	0.0213	±3	15	30	10
20	0.84	0.0331	0.42	0.0165	±5	15	30	25
30*	0.59	0.0232	0.33	0.0130	±5	15	30	25
40	0.42	0.0165	0.25	0.0098	±5	15	30	25
50*	0.297	0.0117	0.188	0.0074	±6	15	35	40
60	0.250	0.0098	0.162	0.0064	±6	15	35	40
80	0.177	0.0070	0.119	0.0047	±6	15	35	40
100*	0.149	0.0059	0.102	0.0040	±6	15	35	40
120	0.125	0.0049	0.086	0.0034	±6	15	35	40
200	0.074	0.0029	0.053	0.0021	±8	15	35	60
325	0.044	0.0017	0.036	0.0014	±8	15	35	90

* Most used sieves. For additional sieves see *A.S.T.M. Standards.*

For coarse aggregate, sieves are made from woven-wire meshing or sheet metal perforated with round holes. The size of opening, generally in the clear, is stated in fractions of an inch. Wooden-rimmed sieves 16 to 20 in. in diameter and 4 in. deep, equipped with meshing or perforated metal varying in diameter of opening as indicated in the upper part of Table 1, are satisfactory.

Before using, all sieves should be carefully calibrated to ascertain the variation in shape and size of openings and the average diameter of the mesh. For fine sieves a linen tester's microscope may be used to count the meshes but a microscope fitted with a graduated eye-piece is necessary to measure accurately the size of the wire. Coarser sieves may be measured by means of micrometer calipers. The most accurate calibrations can be made by shaking materials of known analysis upon the given sieve and determining the per cent passing. The diameter of wire and size of opening in a given sieve should conform to the tolerances specified in Table 1.

In making the mechanical analysis test a representative sample of the aggregate should be dried and weighed on scales accurate and sensitive to 0.1 per cent of the weight of the total sample. For fine aggregate a 500-gram sample is a convenient quantity. Commonly, the sieves are nested in a mechanical shaker, a type of which is shown in Fig. 3, Ch. XII. The sample is poured on the top sieve, the cover secured in place, and the apparatus is run for a length of time which has been found sufficient to separate similar material. For determination on coarse aggregate, a 25- to 50-lb. sample, depending upon the range in size of particles, is sieved by hand, starting with the coarsest sieve.

When weighing, it is best to place the residue on the coarsest sieve in the scale pan first, then add the residue on the next finer sieve, and so on. Thus successive weight readings may be easily converted into percentages retained, and the discrepancy between the final and initial weight of the sample gives a check on losses.

Interpretation of the results of mechanical analyses are readily made by diagrams (see Fig. 4). In these diagrams, percentages by weight passing a given mesh are plotted as ordinates and the diameters of openings in the mesh as abscissas. The *fineness modulus*, *m*, is a less informative but useful measure of the size and grading of an aggregate. It is found by adding the percentages coarser than each of the asterisked sieves listed in Table 1, and dividing the sum by 100. For calculations of *m*, see the table in Art. 470.

463. Yield is used in two senses: (*a*) to indicate the ratio of the volume of mortar or concrete to the loosely measured volume of aggregate in the mix; (*b*) to indicate the volume of mortar or concrete in cubic feet which can be made with a sack of cement. In either sense it is useful in estimating quantities of material for making a given volume of concrete or mortar.

The following method of determining yield has been employed for several years at the University of Wisconsin. The determinations are made in calibrated cylindrical cans. Each of these cans is equipped with a loosely fitting plunger fastened on the end of a piston rod which is so graduated that the volume of the mix may be read in decimals of a cubic foot. Figure 3 shows the large volume can used for determining yield of concrete. About 3 lb. of dry materials are used to determine the yield of mortars and 150 lb. for the determinations on concrete. After the specific weight of the aggregate has been gotten, the requisite amount of each material is weighed and mixed on a non-absorbent mixing board in accordance with a standard method. The mix is then introduced into the cylinder in four layers of equal thickness. In the mortar tests each layer is compacted by an iron tamper having a face $1\frac{5}{8}$ in. in diameter, which is the radius of the inside of the mortar volume can. In the tests on concrete, after the introduction of each layer, the material is puddled with an iron rod and the cylinder is raised 6 in. and dropped on the concrete floor five times to compact the mixture. After the mixing board and tools have been thoroughly cleaned and all material put into the can the plunger is inserted, and whirled around to level the top of the mix. A tripod (t) which carries an index (I) is next slipped over the end of the piston rod and rested on the top of the volume can. The reading on the plunger rod opposite the index on the tripod gives the volume of the mix.

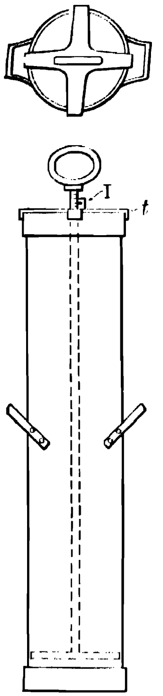

FIG. 3.—Volume Can.

In calculating the results of the test the losses are apportioned in accordance with the amount of each material passing a No. 80 sieve, since experiments have shown that practically all material lost can be washed through this sieve.

✓ **464 Density** * is the ratio of the absolute volume of the solid particles of cement plus aggregate to the volume of the resulting mortar or concrete. If c, s, and g represent the absolute volumes of cement, sand, and gravel, respectively, in a unit volume of concrete, the density $= \rho = c+s+g$. If the specific gravities of the cement and aggregate are known, then the density of a mix may be computed from the results of the yield test as follows: Let $V =$ volume of mix; W_c, W_s, and $W_g =$ the weights of the cement, sand, and gravel, respectively, corrected for losses in mixing;

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* Note that this definition differs from that usually given in treatises on mechanics by excluding the mass of the water. The term solidity ratio, adopted in *Technologic Paper* No. 58 of the U. S. Bureau of Standards, is more exact.

K_c, K_s, and K_g = the specific gravities of the cement, sand, and gravel, respectively; W_w = the weight per cubic unit of water, then

$$p=\frac{1}{W_w V}\left[\frac{W_c}{K_c}+\frac{W_s}{K_s}+\frac{W_g}{K_g}\right].$$

Experiments have shown that the density of a mortar or concrete is a measure of its strength and imperviousness.

CHARACTERISTICS AND PROPERTIES OF FINE AGGREGATE

465. Importance of Good Aggregate.—Although the importance of testing cement has been recognized for a good many years, it is only recently that the necessity for ascertaining the properties of the aggregate has been appreciated. Now, however, with the results of numerous experiments and the records of failures caused by the use of poor aggregate before them, engineers are becoming convinced that a knowledge of the properties of the aggregate is fully as important as a knowledge of the properties of the cement. Inasmuch as fine aggregates of any one type, even those from the same deposit, often differ widely in their characteristics and properties, it is especially desirable to learn as much as possible about them before using in any important work. However, satisfactory test reports on the aggregate do not insure good concrete.

466. Sampling Aggregate.—Due attention must be given to the securing of representative samples of aggregate. If the character of the deposit, or supply of material, is variable, then individual samples of the different grades may well be taken and tested separately, or mixed together, depending upon the degree of variation. For preliminary examinations, the samples of fine aggregate should not weigh less than 25 lb., and samples of coarse aggregate should not be less than 100 lb. For more complete tests or for mix designs, much larger quantities may be required.

In sampling the open face of a sand or gravel pit, the character of the overlying material, the stripping, should be noted and the face of the opening sampled from the bottom to the top. This may be conveniently done by scooping vertical troughs out of the face of the bank with a pail, which should be so manipulated that an equal amount of material is secured from every portion of each trough. If sharply defined strata of fine and coarse particles are present, it is well to secure separate samples of the material composing these layers.

When one is sampling a pile of aggregate, it should be remembered that the coarse particles tend to separate and flow towards the bottom of the pile; consequently it is desirable either to flatten the pile and employ the "method of quartering" (Art. 398) or, if the pile is very large, to proceed in the same manner as suggested in sampling a pit. Standard procedure for sampling aggregates may be found in A.S.T.M., Des. D 75-22.

In selecting portions of a sample of aggregate for the different tests the method of quartering or an equally efficient method should be employed.

467. Requirements for Fine Aggregate.—The fine aggregate should consist of a mixture of hard, tough grains of different sizes. Particles of approximately equal dimensions are preferable to elongated grains; since the former, with similar gradation of sizes, produce more compact mixtures containing less voids than the latter. The sharpness of the grains is of little importance. The fine aggregate should be free from any minerals of a weak, friable nature and from other impurities such as organic or vegetable matter, the presence of which in very small percentages may be very injurious. The presence of 10 per cent or more of clay or loam is, in general, objectionable. Smaller percentages of these impurities may impair the efficiency of fine sands.

Preferably, the percentages of fine aggregate retained on the respective sieves should be limited for general concrete construction as follows: none on a $\frac{3}{8}$-in. sieve, 0 to 5 per cent on a No. 4, 20 to 40 per cent on a No. 16, 75 to 95 per cent on a No. 50, and 92 to 100 per cent on a No. 100 sieve. The fineness modulus, m should usually be between 2.5 and 3.2.

Whenever time permits, strength tests should be made of mortars containing the fine aggregate. In fact, it is unsafe to use sands of unproven quality unless such strength tests are made. A 1 : 3 mortar of standard consistency, made from good sand or screenings, should have a strength at least equal to that of a similar mortar of standard sand made by the same operator. Compression tests are the most valuable, although tension or transverse tests are permissible. If the sand is to be used in making concrete, it should be mixed with the proper proportions of the cement and stone with which it is to be used and the strength of the hardened mixture should be ascertained.*

468. Composition of the Particles.—Although the results of a chemical analysis combined with a knowledge of the mineral content of a fine aggregate is sometimes helpful in determining its value, too great importance is often attached to the chemical analysis of sands. Some experimenters have believed that a very high silica content should be demanded in specifications for fine aggregate. Doubtless a sand which consists principally of hard, tough, and non-porous grains of quartz is superior to a soft, calcareous sand, provided other characteristics are similar. Nevertheless there are many good sands and a variety of suitable broken stone screenings having comparatively low silica contents which make mortars of high strength.

Inasmuch as the strength of the mortar or concrete is dependent upon the strength of the aggregate as well as the strength of the cement, the grains of sand or screenings should, at least, equal the cement in strength.

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* See Art. 485.

Since the resistance of cement paste to attrition and abrasion is small, the resistance of mortar to such influences is largely dependent upon the hardness and toughness of the aggregate. Consequently, whenever high resistance to abrasion is desired the particles of the aggregate should be so hard that they cannot be readily scratched with a pocketknife. If the aggregate is very porous it is likely to withdraw water from the cement during the hardening. This results in the formation of a weak layer of paste surrounding the grains.

From a consideration of the above facts, it is, therefore, evident that the presence of a large proportion of hard, tough, dense minerals which are not readily attacked by atmospheric conditions is a favorable indication of the quality of an aggregate. If porous, the aggregate should be thoroughly soaked with water before mixing with cement.

Some of the more desirable mineral constituents are quartz, dolomite, and hornblende. Among the objectionable are mica, talc, iron pyrites, shale, limonite, ochre, hematite, and the absorbent types of chert. Most of these weather badly under freezing and thawing, as shown by R. R. Litehiser before the National Sand and Gravel Association in 1938.

469. Impurities.—The effects of natural impurities like clay and loam are dependent upon: 1, the gradation of the sand particles; 2, the richness of the mortar; 3, the chemical constitution and the fineness of the particles in the clay or loam. Lumps of clay or loam are decidedly harmful. Their weight should not exceed 1 per cent of the fine aggregate. The addition of finely ground clay to a coarse sand may improve its grading and reduce voids. Hence lean mortars deficient in fines may be improved both in density and in plasticity by additions of small percentages of such clays.* A rough qualitative test for detecting small percentages of loam or clay may be made by rubbing the sand between the palms and noting the amount and character of the stain thus produced. If present in large percentages clay imparts a greasy, slippery feeling to the sand when it is wetted and loam is generally readily detected by its dark color.

Coal and lignite should not be permitted in excess of ¼ per cent. For concrete subjected to abrasion, the amount of material in the aggregate passing a No. 200 sieve should be under 2 per cent. Alkali, mica, coated grains, and soft particles should not exceed 1 per cent, and the weight of all impurities should not exceed 3 per cent of the fine aggregate.

Organic and vegetable impurities, which often injure the hardening properties of the cement, are usually found in the silt. Hence sands containing more than 6 per cent by volume, or 3 per cent by weight, are likely to be unsatisfactory and should always be subjected to a mortar strength test before using.

In 1916 Messrs. D. A. Abrams and O. E. Harder perfected a colori-

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* See paper by Withey and Wendt, *Proc. A.S.T.M.*, Vol. 35, Pt. 2, p. 426.

metric tests for organic impurities in sands which may be carried out in the field as follows:

"Fill a 12-oz. graduated prescription bottle to the 4½-oz. mark with the sand to be tested. Add a 3 per cent solution of sodium hydroxide until the volume of the sand and solution, after shaking, amounts to 7 oz. Shake thoroughly and let stand over night. Observe the color of the clear supernatant liquid. . . . If the clear supernatant liquid is colorless, or has a light yellow color, the sand may be considered satisfactory in so far as organic impurities are concerned. On the other hand, if a dark-colored solution, ranging from dark reds to black is obtained, the sand should be rejected or used only after it has been subjected to the usual mortar strength tests.

"Field tests made in this way are not expected to give quantitative results, but will be found useful in: (1) Prospecting for sand supplies; (2) Checking the quality of sand received on the job; (3) Preliminary examination of sands in the laboratory." *

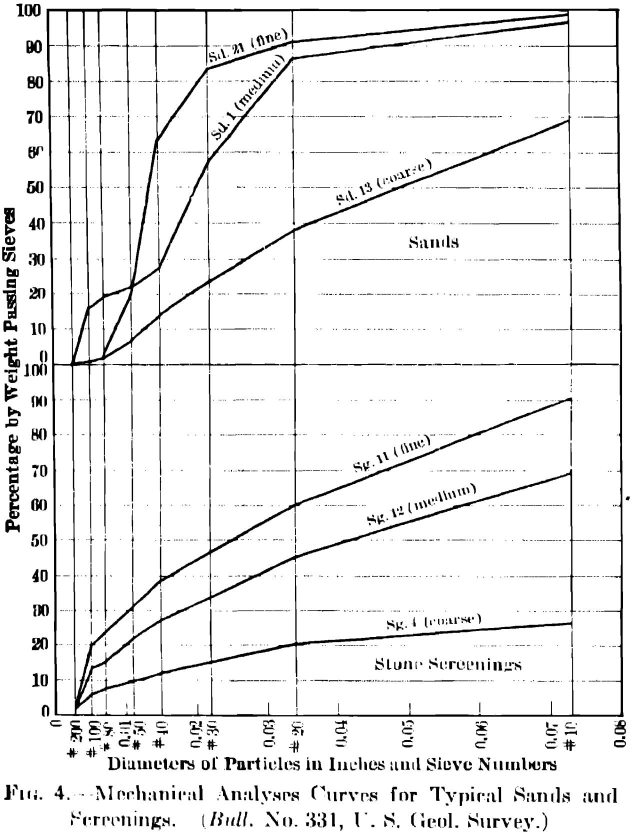

FIG. 4.—Mechanical Analyses Curves for Typical Sands and Screenings. (*Bull.* No. 331, U. S. Geol. Survey.)

470. Gradation of the Sizes of the Particles.—Experiments have indicated that mortars made from fine sands are less dense and strong than those made from coarse sands. This is probably due to two causes: first, the difficulty of coating very fine particles of sand with cement particles of like size and second, the larger percentage of voids in the mixture of fine sand and cement. Experiments have also shown that the most effective gradation of the sizes of the particles is dependent upon the richness of the mix and the maximum size of the aggregate.

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* For laboratory methods of quantitatively determining the organic material present in sands see Circular No. 1, Structural Materials Research Laboratory of Lewis Institute, from which the above description was taken.

A good conception of the gradation of the sizes of aggregate particles is afforded by mechanical analysis diagrams coupled with values of the *fineness modulus, m* (see Fig. 4 and the following table). Whereas the fineness modulus per se gives no indications of gaps in grading, it is the best of the simple indices thus far devised for measuring grading. For studies of the effects of particle interference, reference should be made to the work of C. A. G. Weymouth (*Proc. A.S.T.M.*, Vol. 38, Pt. 2, p. 354).

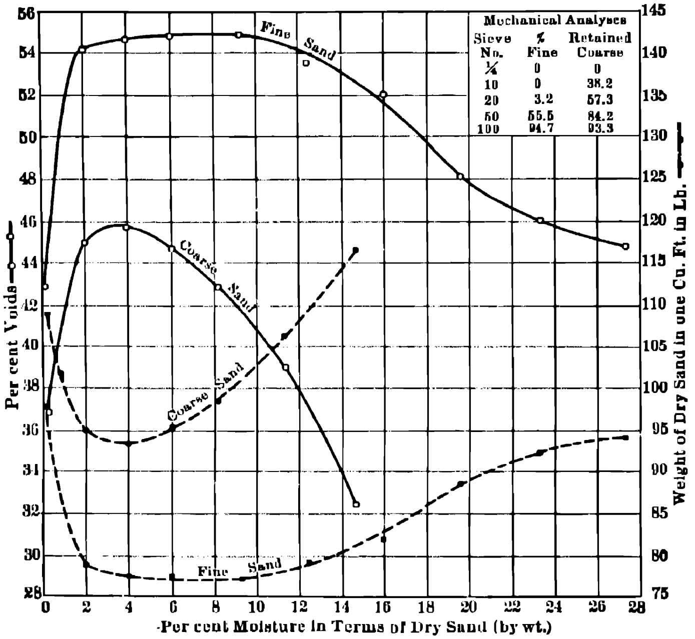
Sieve No.	Diameter Opening (In.)	Percentage Coarser than Sieve for Aggregate					
		Sd 13	Sd 1	Sd 21	Sg 4	Sg 11	Sg 12
4	.187	0	0	0	0	0	0
8	.094	20	5	0	60	5	20
16	.047	55	12	7	78	48	32
30	.0232	77	45	16	84	66	52
50	.0117	92	78	73	90	77	67
100	.0059	99	84	84	95	87	80
Fineness modulus (m).		3.43	2.24	1.80	4.07	2.83	2.51
Gradation		Coarse	Medium	Fine	Coarse	Medium	Fine

The results of strength tests of mortars made of these fine aggregates are given in Table 1, Chapter XIV. Sand Sd 1 of medium gradation is preferable to either of the other sands for making concrete of usual proportions but inferior to sand Sd 13 for making a strong mortar. Sand Sd 13, on the other hand, would produce a harsh working concrete unless a high content of cement were used. Sand Sd 21 is too finely graded to make the most efficient concrete or mortar. Beach sands are often graded like it. Coarse sands like Sd 13 are rarely found.

Broken stone screenings should not contain over 10 per cent of dust passing a No. 100 sieve nor more than 25 per cent of particles passing a No. 50 sieve. Large amounts of crusher dust are especially objectionable when the screenings are to be used for tops of floors or sidewalks, since mortars containing large percentages of dust are likely to wear badly.

471. Voids and Specific Weight.—Two other criteria of the worth of sands and screenings are afforded by the percentage of voids and the specific weight. Approximately, we may say that for fine aggregates of like chemical and mineral constitution those with the lowest percentage of voids or the highest specific weight are the most desirable, since a less proportion of cement will be required to fill the unoccupied space in such aggregate. One must bear in mind, however, that due to differences in gradation two sands which contain the same percentage of voids may produce mortars differing considerably in density and strength. For instance, comparing a fine and a coarse sand containing the same proportion of voids, the coarse sand will produce the stronger mortar.

Since even a small percentage of moisture tends to hold apart the grains and increase the voids, the moisture content exercises a very important influence upon the percentage of voids and the specific weight. For examples examine Fig. 5, which shows the effect of the percentage of moisture upon the voids and specific weights for a fine and a coarse sand. The curves in the diagram serve to illustrate the importance of making the determinations on material containing the per cent moisture ordinarily present in field operations, if the results are to be employed in the field. If, however, a comparison of different sands is to be made determinations should also be conducted upon dried aggregate.



Mechanical Analyses

Sieve No.	% Fine	Retained Coarse
¼	0	0
10	0	38.2
20	3.2	57.3
50	55.5	84.2
100	94.7	93.3

FIG. 5.—The Effects of Moisture on the Voids and Specific Weight of a Fine and a Coarse Sand.

To facilitate the computation of the percentage of voids from the specific weights, the diagram in Fig. 6 is provided. Since a knowledge of the specific gravity of the aggregate is necessary in order to use this diagram the following average values are given for sands: Quartz, 2.65; dolomitic sands, 2.65–2.75; calcareous sands, 2.60–2.70. A rough average value for all sands is 2.65. For specific gravities of stones, see Art. 268.

For good sands the percentage of voids generally lies between 28 and 35. The corresponding weights per cubic foot range from 120 to 105 lb. In screenings, on account of the angular shape of the particles, a somewhat higher range in the percentage of voids is to be expected. Screenings of good quality should not, in general, contain over 38 per cent voids.

472. Mortar Tests.—By far the most valuable indices of the efficiency of a fine aggregate are given by the strength and yield tests of mortars made with a cement of known properties.

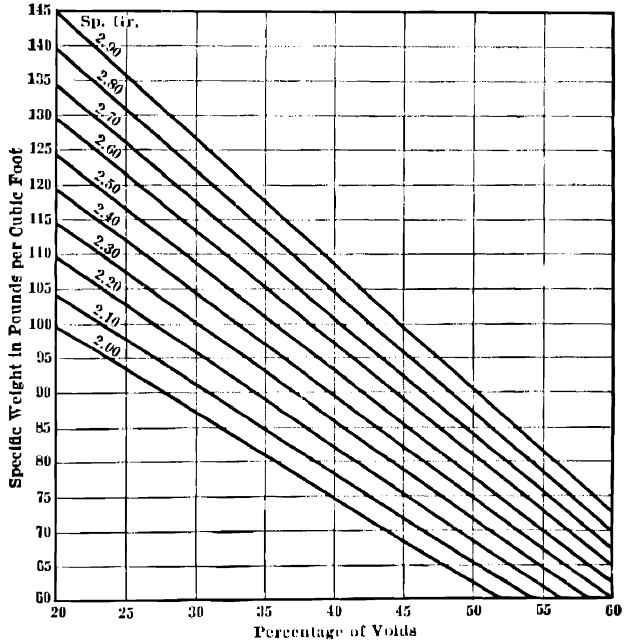


FIG. 6.—Relation of Specific Weight to Voids.

Usual procedure in determining quality of fine aggregate is to compare the strength of an Ottawa sand mortar with the strength of a similarly made mortar of the given sand. In practice, however, there is considerable difference in the kind of test, the grading of Ottawa sand, proportions and consistency of mix, and method of procedure specified.

In specifications there is a tendency to require a 10-in. flow table, using 30 $\frac{1}{8}$-in. drops in 30 sec. for making consistency comparisons (see Art. 447).

Where a flow table is not available the following method may be used. Proceed in the standard manner indicated in Art. 414 and mix a batch of 500 or 600 grams of mortar. Cover with a bowl. Proceed in like manner with a batch of the same proportions containing the given sand or screenings. In estimating the required amount of water for the latter batch, it should be remembered that natural sand or screenings will generally require 10 to 50 per cent more water than standard sand, and that the percentage of water required varies with the proportion of fine material in the aggregate. Two or three trials will ordinarily suffice to obtain the consistency which appears and feels like that of the standard sand mortar.

For comparing the strength of the given sand with that of Ottawa sand, the following procedure is suggested. Use Ottawa sand, about half standard and half run of mine, with a fineness modulus between 2.3 and 2.5. Adopt 1 : 2.75 proportions, by weight, of cement to sand for both sands. Use sufficient water with each mix to give a flow, under the above procedure, between 60 and 75 per cent. For the strength comparison at least 3 specimens of each kind of sand should be tested at 3 and 7, or at 7 and 28 days. The compression test on 2-in. cubes is preferable to the briquet test.

The following mortar test is suggested as an inexpensive test to predict the strength of concrete which can be made with a given sand. Mold and cure in standard manner five 2 by 2 by 9-in. mortar prisms of the given sand. Test at 3 or 7 days first as beams under center loading; then test the halves as modified cubes (Art. 113). For these tests a fixed water-cement ratio, 0.5 by weight, should be used. A considerable amount of testing for a thesis by P. J. Hunt, C. D. Matthias, J. L. Shipman, and E. C. Wagner at the University of Wisconsin, 1936, indicated that this procedure has merit in predicting either the compressive strength or the modulus of rupture of gravel concrete of the same water-cement ratio and age as the mortar.

Sands to be used in mortars for construction purposes should possess at least 85 per cent of the strength of standard sand mortars of like proportions and consistency.

The yield test on a mortar is often made to ascertain both the yield and the density. The density is a more reliable index of the mortar strength than is the voids in the fine aggregate. In general, the density of a 1 : 2 or 1 : 3 mortar, by weight, made with well-graded sand and mixed to standard consistency used in cement testing will lie between 0.70 and 0.75; the yield will generally vary between 1.08 and 1.20 for similar mixes, being greater for the richer mix.

CHARACTERISTICS AND PROPERTIES OF COARSE AGGREGATE

✓ **473. Requirements for Coarse Aggregate.**—Any stone or gravel which possesses the strength of neat cement is sufficiently strong for use as an aggregate. In hardness, however, there is a considerable range permissible, depending upon the kind of construction. In floors, pavements, and other surfaces subjected to considerable wear and upon which no top dressing is placed, a uniformly hard and tough coarse aggregate which will show less than 30 per cent loss in the Los Angeles rattler test (Art. 273) is desired. For other constructions extreme hardness is not essential provided the aggregate shows a rattler loss under 40 per cent.

The coarse aggregate should also be free from loam, clay, vegetable or organic matter, and other injurious substances previously mentioned under fine aggregates. More than 1 per cent of shale is objectionable. Clay lumps should not exceed ¼ per cent.

Preferably, the particles of the aggregate should be approximately cubical or spherical in form. Flat, disc-shaped pieces and long, thin wedge-like particles are objectionable since they cannot be so closely compacted as the cubical or rounded stones. To secure a good bond between the mortar and the coarse aggregate, the cleavage planes of broken stone and the surfaces of gravel particles should be uneven and rough. Very porous particles must be saturated with water before mixing with cement.

In a well-graded coarse aggregate 95 per cent or more should pass the sieve of maximum permissible size of opening, 30 to 70 per cent should pass the sieve of half that size of opening (the mean sieve), and not over 10 per cent should pass the No. 4 sieve. The maximum permissible size of aggregate depends upon the type of construction, but it rarely exceeds 2½ in. in diameter. The maximum diameter of particle should not exceed one-fifth of the minimum width of form. In reinforced work it should not be larger than three-fourths of the clear spacing of reinforcing.

For economical production of both fine and coarse aggregate, pit-run gravel should contain 50 per cent or over of coarse aggregate.

Measured loose the voids in well-shaped broken stone range between 45 and 50 per cent; if uniformly varying in gradation, between 40 and 50 per cent. For loosely measured gravel varying from ¼ in. to 1½ in. in diameter the voids vary from 35 to 40 per cent. In dry well-graded pit-run gravel, voids run under 28 per cent. When rodded in measuring, the voids will be approximately 4 to 5 per cent less than the above data.

474. Characteristics and Properties of Broken Stone.—The broken stones commonly used for coarse aggregate are trap rock, granite, dolomite, limestone and sandstone. Trap rock, on account of its hardness, toughness, high resistance to fire, and great strength, is an excellent coarse aggregate. The granites also furnish a very good material for coarse aggregate. Both of these classes of rock are very desirable in road or floor construction, or on surfaces which are subjected to considerable abrasion. Oftentimes, however, these hard igneous rocks crush into elongated particles which cannot be closely compacted. Consequently maximum density cannnot be secured in the concrete or mortar into which they are made. When such aggregates have very smooth cleavage planes, the mortar will not strongly adhere to the surfaces and the resulting concrete will be deficient in strength. In spite of these objections, however, these rocks form the most valuable class of crushed aggregates.

Crushed dolomite and limestone are extensively used for coarse aggregate. Although softer than the granites and traps, the dolomites and hard limestones make concrete which is as strong as, and which resists fire better than concrete made of granite. Usually limestone concrete wears more uniformly than concrete made of igneous rocks. Soft limestone is often very porous, and unless thoroughly wetted before mixing will weaken the strength of the surrounding mortar by absorbing water from it while the hardening process is going on. Limestones frequently contain large quantities of very fine dust which, in wet weather, coat the surfaces of the stones. If there is a large proportion of this dust in the coarse aggregate, and if a fine sand is being used, it may be necessary to screen out the dust in order to secure a concrete of high strength. However, if the sand is coarse, allowance may be made for this dust in proportioning.

The stronger and more dense sandstones make a satisfactory coarse aggregate, but the soft varieties together with the shales and slates should not be used. The latter are likely to be deficient in strength and to consist of particles which are improperly shaped for making dense concrete.

Table 2 contains a summary of voids and specific weight tests conducted by Professor I. O. Baker.* These data show the effect of hauling in wagon or car in compacting these aggregates. The data in Table 3 has been compiled from various reports. One can compute voids or specific weight of a given aggregate if either of them and the specific gravity (Art. 268) are known.

On account of the tendency of the stone to separate from concrete when a uniform size of coarse aggregate is used, it seems preferable to use graded mixtures. Furthermore, with graded mixtures the voids in the aggregate are less than in aggregate of uniform size, and concrete made of the graded mixtures is fully as strong and dense as that made of the one-size coarse aggregate. On the other hand, it is doubtful if the uniformly varying gradation often advocated is superior to other gradings differing considerably from it. For example, in Fig. 7 compare the range in gradings for crushed limestone between $\frac{7}{64}$ and $2\frac{1}{4}$-in. sieves ($\frac{1}{8}$ and $2\frac{1}{2}$-in. round openings), all of which Goldbeck † found to have approximately equal voids, with curve U for crushed stone varying uniformly in gradation over the same range in sizes. However, to conserve work-

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* *Bull.* No. 23 Univ. of Ill. Eng. Expt. Sta., 1908.

† From *The Crushed Stone Journal*, September, 1928. Voids are for rodded volumes. For loose volumes voids were about 1.1 times the voids in Fig. 7.

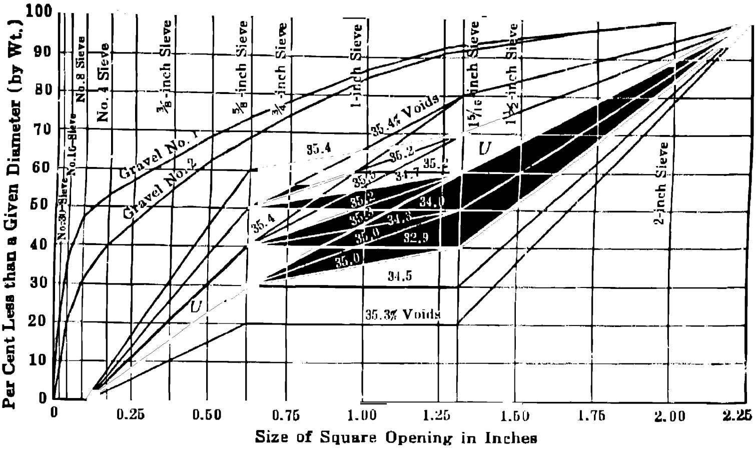

FIG. 7.—Sieve Analysis Curves for Typical Pit-run Gravels and for Broken Stone.

ability the omission of intermediate sizes should be avoided. Reasonable tolerances in gradation, such as suggested in Art. 473, will yield low-void aggregates and lessen costs.

TABLE 2.—PERCENTAGES OF VOIDS AND WEIGHTS PER CUBIC YARD OF CRUSHED LIMESTONE. (BAKER) *

Locality in Illinois.	Size of Stone.	Per Cent Voids.		Weights in Lb. per Cu.yd.			
				Wagon Loads.		Car Loads.	
		By Pouring in Water.	From Specific Gravity.	At Crusher.	After Hauling ½ Mile or More.	At Crusher.	After Hauling 75 Miles or More.
Chester....	⅜-in. scr.	40.9	46.8				
Chester....	¾-in. scr.	43.0	45.6	2442	2797	2546	2850
Chester....	2-in. to ¾-in.	46.6	46.6	2344	2582		
Chester....	3-in. to 2-in.	46.1	45.1	2367	2569	2348	2545
Joliet......	½-in. scr.	42.2	47.1	2303	2533	2659	2905
Joliet......	2-in. to ½ in.	47.9	46.2	2315	2480	2386	2592
Joliet......	3-in. to 2-in.	47.5	46.1	......	......	2361	2553
Kankakee..	⅜-in. scr.	39.6	46.1	2430	2697		
Kankakee..	1¼-in. to ⅜-in.	45.7	44.7	2325	2546		
Kankakee..	2¼-in. to ⅜-in.	44.3	42.9				
Kankakee..	2¼-in. to 1¼-in.	46.2	43.4				

* Each value of per cent voids represents a number of tests in which size of vessel varied from 0.7 cu.ft to 27 cu.ft. and the height of drop of materials varied up to 20 ft. Percentages of absorption (by weight) for these limestones were Joliet, 0.64;. Kankakee, 1.84; Chester, 1.01. Average values of specific gravity were Joliet, 2.71; Kankakee, 2.61; Chester 2.57.

TABLE 3.—VOIDS AND SPECIFIC WEIGHTS OF COARSE AGGREGATES

Kind of Aggregate.	Range in Sizes.	Specific Gravity.	Weight per Cu.ft. (Lb.)	Per Cent Voids.	Authority.
Trap	¼-in. scr.	2.90	98.1	46.5	W. E. McClintock
Trap	1½-in. to ½-in.	2.90	90.0	50.2	W. E. McClintock
Trap	3-in. to 1½-in.	2.90	93.5	48.1	W. E. McClintock
Quartzite	¼-in. scr.	2.67	92.8	44.3	M. O. Withey
Quartzite	1½-in. to ¼-in.	2.67	86.4	48.1	M. O. Withey
Granite	¼-in. scr.	2.62	95.0	41.8	M. O. Withey
Granite	¾-in. to ¼-in.	2.62	86.5	47.0	M. O. Withey
Granite	1¼-in. to ¼-in.	2.62	88.9	45.6	M. O. Withey
Granite	2-in. to ¼-in.	2.62	84.7	48.1	M. O. Withey
Granite	1-in. to dust	2.58	95.3	40.9	U. S. Geol. Sur.
Limestone	1-in. to dust	2.49	97.7	37.1	U. S. Geol. Sur.
Gravel	1-in. to ¼-in.	2.45	102.4	33.0	U. S. Geol. Sur.
Gravel	1½-in. to ¼-in.	2.77	110.5	36.0	M. O. Withey
Gravel (Pit-run)	1½-in. to dust 51% < ¼-in.	2.77	125.9	27.0	M. O. Withey
Gravel (Lake)	1-in. to No. 10	2.75	112.5	34.4	M. O. Withey
Gravel	⅝-in. to ¼-in.	2.70	105.0	37.7	M. O. Withey
Gravel	1¼-in. to ¼-in.	2.70	102.4	39.2	M. O. Withey
Cinders	1¼-in. to dust 37% < ¼-in.	1.53	47.0	50.7	U. S. G. S.
Bank slag	$\frac{3}{16}$-in. scr.	......	117.0	......	Carnegie Steel Co.
Bank slag	1-in. to ½-in.	......	67.0	......	Carnegie Steel Co.
Bank slag	2½-in. to 1-in.	......	72.0	......	Carnegie Steel Co.
Machine slag	2-in. to 1-in.	......	96.0	......	Carnegie Steel Co.

Since stronger and denser concrete can be made from broken stone well-graded from 2½ in. down to ¼ in. than from similar material less than 1 in. in size, the use of rather large coarse aggregate is often economical. When such coarse aggregate is used, uniformity in the grading in successive batches will be conserved by screening the coarse aggregate into two sizes and measuring them separately prior to mixing. Such procedure will promote uniformity in the workability, strength, and watertightness of the concrete.

475. Characteristics and Properties of Gravels.—The statements previously made in regard to the mineral composition of sands apply equally well to gravels. For concrete pavement subjected to heavy traffic all particles should be of uniform hardness. They should not be scratched by the knife. Somewhat softer material may be employed in making concrete for constructions where strength is the only requisite. Gravels containing considerable proportions of disintegrated rock, pebbles coated with soft limestone, clay, or loam should be avoided. Organic matter even in small percentages is very objectionable. Such impurities are often present in gravels gotten from pits in which the overlaying material is covered with leaves and decayed timber. It is possible, however, to remove loam, clay and organic material by thorough washing.

The particles composing the gravel should be approximately round; flat, disc-shaped particles are undesirable since the latter do not compact into as dense mixtures as the former.

Pit-run gravel generally contains too much material passing a $\frac{1}{4}$-in. sieve. Since the gradation of sizes in material from a given pit is often quite variable, as shown by curves for gravel No. 1 and No. 2, Fig. 7; it is difficult to maintain a uniform quality of concrete when pit-run material is used. Hence, whenever considerable gravel is to be used, better concrete and economy in the use of cement will be promoted by screening the pit-run into two or more sizes and recombining in proportions desired in making concrete. Gravel coarse aggregate should conform to requirements suggested in Art. 473.

Boulders of hard, dense rock may often be economically employed, especially in massive walls, abutments and dams, provided the interstices are thoroughly filled with concrete composed of smaller stones. It is desirable to keep such large rocks back from the surfaces of the work since thin outside shells of concrete sometimes spall off, especially if they are poorly bonded and are subjected to frost action.

The voids and specific weights of a number of gravels differing in gradation are given in Table 3. Average values of specific gravity for the different classes of gravel commonly found are approximately the same as the values given for sands in Art. 471.

476. Broken Stone and Gravel Compared.—On account of the spherical shape of its particles gravel makes a more fluid and dense concrete than does broken stone. Furthermore, gravel concrete requires less tamping or puddling than concrete made of broken stone in order to expel entrained air and thoroughly compact the mixture. Considering mixes of concrete of like cement contents and workabilities, those made with well-graded crushed limestones or slags usually exhibit higher cross-bending strengths than concretes made of equally well-graded gravels. On the whole, if equal care is taken in grading the particles of aggregate, gravel concrete seems to be more impervious to water than broken stone concrete. One of the main advantages in using broken stone for concrete is the possibility of securing a product which is of fairly uniform composition.

477. Miscellaneous Aggregates.—Cinders, slag, crushed burnt clay, and mine tailings are also used as concrete aggregates. Cinders resist high temperatures fairly well and have been employed considerably for making fireproof concrete. For this purpose the cinders should be a hard, vitreous clinker, practically free from sulphur, iron oxide, and combustible substances. From the standpoint of fireproofing, a highly porous clinker is desirable. The clinker should be drenched before mixing so that it will not absorb water from the mortar during the process of hardening. Cinders make a very light concrete but should not be employed in constructions demanding high strength or imperviousness to water.

Slag has been used to some extent both as fine and as coarse aggregate. It is an efficient aggregate for fireproofing. For concrete aggregate molten slag from the furnace is run into pits, or onto suitable banks, where it air cools into a dense, hard mass. It is then excavated, crushed, and screened into desired sizes. Slag sand is the finely crushed material passing a No. 4 sieve. Slag coarse aggregates which are sufficiently hard, tough, and durable for highway pavements should weigh not less than 70 lb. per cu. ft., by rodded volume. Extremely light and porous slag aggregates are also produced commercially by a steam centrifuge process.

By burning clay containing organic matter at 1800 to 2000° F., it is inflated and rendered porous. After cooling, crushing, and screening, this product makes an excellent fire resistant aggregate from which a strong concrete weighing only 100 lb. per cu. ft. can be made.

Tailings from zinc and lead mines have been considerably used in Missouri and southwestern Wisconsin for concrete aggregate. The chief objection to these aggregates is the presence of pyrites, which causes rust-like spots on the surface of the concrete.

THE PROPORTIONING OF MORTARS AND CONCRETES

478. The Principles of Proportioning.—The fundamental object in proportioning concrete or mortar mixes is the production of a durable material of requisite strength, watertightness and other essential properties at minimum cost. To attain this end, careful attention must be given to the selection of cement, aggregate, and water in accordance with preceding principles, and to the following considerations:

1. The mix must be workable so that it can be placed and finished without undue labor.*

2. Since cement is the most costly ingredient in the mix, the proportion used should be as small as is consistent with the attainment of desired properties.

3. Within wide limits, experiments have shown:

(*a*) The strength and degree of watertightness of mixes, having like constituent materials, density, and workability, increase with the cement content.

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* There is no simple method for measuring workability which is entirely satisfactory. Usually the slump, or flow, of the mix is specified (Art. 485), but either is really a criterion of consistency. The ease with which a mix can be worked and surfaced with a trowel affords a rough index of workability. Unfortunately, personal equation and experience exert a powerful influence in such determinations.

(*b*) With the cement content, materials, and workability all constant, the strength and degree of watertightness increase with the density of the mix.

(*c*) For usual methods of placement, the strength and degree of watertightness of well-cured concrete and mortar are greatest when the mix is plastic (has a slump of approximately two inches). Drier mixes, although frequently as strong, are likely to be porous unless compacted by pneumatic rammers or electrically driven vibrators. Increasing the water content beyond that required for plasticity causes the strength to decrease rapidly.

In addition to the above, the following statements appear to be justified by the results of experience and tests:

(*a*) To proportion concrete for the maximum resistance to fire, a porous non-combustible aggregate of high specific heat together with cement sufficient to produce the requisite strength should be thoroughly mixed and placed with as little ramming as possible to produce a porous concrete.

(*b*) In proportioning concrete or mortar which is to be subjected to freezing temperatures, a minimum amount of water should be used and a quick-setting cement. (Arts. 371 and 539.)

(*c*) Concrete for road construction should be made from a carefully graded, hard tough aggregate bound together with as small a proportion of rich mortar as is consistent with the required workability, strength, and imperviousness.

The principal schemes used in scientific proportioning of mixes are based upon relationships between properties and ratio of cement to voids in the mix, or on the relationship between properties and the ratio of water to cement in the mix.

479. The Measurement of Proportions.—The most accurate method of measuring proportions is to weigh the required quantities of each material. This may be done whether the proportions are based upon volumes or weights. This method is being extensively used in road construction and in many central mixing and in central proportioning plants. Unfortunately, it has not been so widely adopted in building construction where the less accurate method of measuring proportions by volumes is still largely used. The chief inaccuracies in volumetric measurement arise from the wide variations in the bulk of the fine aggregate due to small changes in its moisture content and faulty methods of filling measuring devices. If a careful check is maintained both on the measures and methods of filling, much of the error in volumetric measurement can be obviated. Cement is usually measured by the bag, assuming each bag contains 1 cu. ft. or 94 lb. More accuracy is obtained by weighing the cement also.

480. Arbitrarily Selected Proportions.—Probably the most used method of proportioning is that based upon arbitrary selection. In specifying proportions for mortars it is common practice to call for 1 : 2, 1 : 3 or 1 : 4 parts of cement to parts of fine aggregate, depending upon the quality of mortar demanded. In proportioning concrete by this method, the engineer, guided by experience and a knowledge of the requirements for the structure, assumes a mortar of given proportions and selects a proportion of stone such that the voids in the stone, as measured at the job, will be 15 to 25 per cent less than the volume of the mortar. Such methods or proportioning may give very fair results when used by a man experienced in judging aggregate, but in the hands of a person inexperienced in their use a poor mix or a waste of cement is likely to result.

481. Proportions Based on Voids.—A great variety of rules for proportioning based upon the principle of filling the voids in the aggregate with cement have been formulated. There are two main reasons why such rules are not accurate. First, the problem of wetting the aggregate and bringing it into the same state of compactness which it assumes in the concrete or mortar is very difficult of solution; second, the general assumption that the particles of cement will fit into the void spaces in aggregate is fallacious, especially if particles passing a No. 50 sieve are present in the aggregate.

More satisfactory methods of mix design have been developed from the relation of the strength to the cement content and density of the mix. Thus Talbot and Richart * evolved a scientific and reliable method of mix design based upon a knowledge of the following factors:

1. The relation of strength of concrete to the cement-void ratio;

2. The relation of voids in mortar used in the concrete to the water content of the mortar;

3. The relation of the voids in the mortar to the ratio of the absolute volumes of sand and cement contained in the mortar.

This method is fundamentally sound and accurate but it requires the determination of more experimental data than does the water-cement ratio method which follows:

482. Proportioning by the Water-Cement Ratio Method.—In 1918 Abrams † established the validity of the following simple but very valuable law:

For placeable mixes made from durable aggregates the strength depends upon the net ratio of the mixing water to the cement. The net ratio is based upon the amount of water free to combine with the cement when setting begins. The water-cement ratio has been commonly computed by volume, but the weight ratio is handier in designing mixes.

Later it was shown that the water-cement ratio (x) bears a direct linear relation to the ratio of the volume of cement plus voids to the volume of cement $\left(\frac{v+c}{c}\right)$.* Hence it follows that this law expresses in an inverse manner the previously stated principle that the strength depends upon the ratio of the cement to the space in the concrete unoccupied by aggregate. The advantage of this law is its simplicity and its comparative independence of other variables. Success in the application of this method depends upon the care taken (*a*) in selecting materials; (*b*) in obtaining proper placeability with the use of minimum amount of cement; (*c*) in determining accurately the relation of the water-cement ratio to the desired property for the materials at hand; (*d*) in controlling the measurement of materials, especially the cement and water, at the job. The procedure is illustrated by the steps in the solution of the following typical example in which it is assumed that selection of materials has been made:

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* *Bulletin* No. 137, Engineering Expt. Sta., University of Illinois.

† *Bulletin* No. 1, Structural Materials Laboratory, Lewis Institute.

Example.—A concrete pavement is to be built in a northern climate. In order to resist frost action and to withstand traffic and other conditions, the concrete is to be made with a compressive strength of 3500 lb. per sq. in. at 28 days. For workability a 2-in. slump is desired. The materials required per cubic yard of concrete, and proportions are required.

The available coarse aggregate is a dolomitic gravel, all of which passes a 1½-in. sieve, 40 per cent passes a ¾-in. sieve, and all is held on a No. 4 sieve. The available sand is of good quality; it passes a No. 4 sieve and has a fineness modulus of 2.7. The specific weight of the gravel containing 1.5 per cent moisture and measured loose is 102 lb. per cu. ft.; the specific weight of the sand measured loose with 3 per cent moisture, the normal content in stock pile, is 92 lb. per cu. ft. Costs are: cement, $2.50 per bbl. (376 lb. net); sand, air-dry, $1.60 per ton; gravel, air-dry, $1.80 per ton.

Solution.—In order to determine the proper water-cement ratio (x) one may enter Abrams' curve between compressive strength (C) and the water-ratio (Abrams' C-x curve in Fig. 8) with the given strength and find x. Then a paste may be made with the given water-cement ratio (x) and, by trial, sand and gravel may be added to that paste until the desired workability is obtained. From the quantities used the mix proportions may be determined. The procedure is satisfactory for small jobs when the materials are of good quality. On large jobs or on work where the aggregates are unknown, it is best to find by trial the C-x curve for the available materials.

For the materials of this problem the strength-water-ratio (C-x) curve shown in Fig. 8 was constructed as follows:

Four values of the water ratio (x) were selected to cover the range in concrete strength likely to be used. For the mix of lowest water-ratio a paste consisting of 25 lb. of cement and 10 lb. of water was thoroughly mixed and several additions of *air-dry* sand and gravel were made. In such procedure the endeavor was to use as much coarse aggregate and as little sand as possible, thereby promoting economy. On the other hand, if too little sand was used the mix became harsh and unworkable. Hence, if the mass, when worked with the trowel, appeared too harsh, more sand was added; or, if it appeared over sanded, more stone was added. Finally after the sand and gravel additions amounted to 30 and 82 lb., respectively, the slump was tested and found to be 1½ in. Since the absorption of the sand (for method of finding, see Art. 483) was 0.6 per cent and of the gravel 0.4 per cent, the water absorbed by both was 0.5 lb. Hence the water free to combine with the cement was 10 − 0.5 = 9.5 lb. and x = 9.5 ÷ 25 = 0.38. The volume of the concrete was determined and then the batch was made into three 6 by 12-in. cylinders in accordance with standard procedure (Art. 485). Similarly the three other batches were made and moulded into cylinders. On important work the number of batches should be doubled to reduce errors. After curing 1 day in molds and 27 days in moist air all cylinders were broken and the strength-water-ratio (C-x) curve plotted (Fig. 8). From the weights of materials and measured volumes of batches, the cement contents and specific weights for the fresh concrete were computed. These data made possible the plots of the strength-cement-content(C-c) curve and the weight-water-ratio (W-x) curves for 2-in. slump. The ratios of sand to total aggregate by weight were computed and plotted against the water ratio forming the S-x curve for 2-in. slump.

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* Report of Committee C-9, Proc. A.S.T.M., Vol. 27, Part I, p. 370.

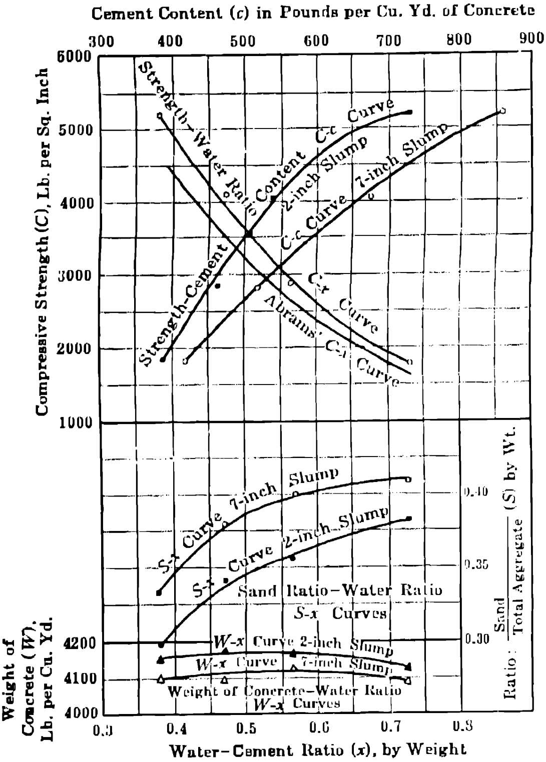

FIG. 8.—Example Diagrams for Designing Concrete Mixes Using the Strength-Water-Cement-Ratio Relationship.

Entering the C-x curve with C = 3500 lb./in.², x is found to be 0.51, by weight. Entering the C-c curve for 2-in. slump with C = 3500, the cement content (c) is found to be 500 lb. per cu. yd. of concrete. From the W-x curve for 2-in. slump, the weight of the concrete for x = 0.51 is 4170 lb. per cu. yd. From the S-x curve for 2-in. slump the ratio of the sand to total aggregate is 0.35. Hence the quantities for 1 cu. yd. of concrete with air-dry aggregates and the cost of materials only are:

Material	Weight in Pounds	Cost in Dollars	
		Per Pound	Total
Cement.	500	.00665	3.32
Water.	0.51 × 500 = 255		
Sand.	0.35(4170 − 755) ÷ 1.006 = 1188	.00080	0.95
Gravel.	0.65(4170 − 755) ÷ 1.004 = 2211	.00090	1.99
Absorbed water. .	1188 × .006 + 2211 × .004 = 16		
Total.	4170	. . . . . .	6.26

The allowances for moisture in the sand and gravel per cu. yd. of concrete are:

Sand weight with 3% moisture		1224 lb.
Gravel weight with 1.5% moisture		2244 lb.
Water required	255 lb.	
Excess water in sand, 1188 (0.03–0.006)	−29	
Excess water in gravel, 2211(0.015–0.004)	−24	
Water to be added		202 lb.
Cement		500 lb.
Total weight of materials per cu. yd.		4170 lb.

On a one-sack basis, with aggregates moist, the proportions by weight are obtained by dividing each of the above quantities by 500 ÷ 94 = 5.32. Hence with one sack of cement there would be required 230 lb. of sand, 422 lb. of gravel, and 38 lb. of water. By volume, measured loose, the proportions would be $1 : \frac{230}{92} : \frac{422}{102} = 1 : 2.5 : 4.14$ with 4.5 gal. of water per sack of cement.

Trial of the above mix in a mixer might reveal deficiencies in working qualities or it might indicate that slightly less sand and more gravel could be economically used.

For many types of building construction more workable mixes than those just determined and more fluid consistencies are desirable. Hence the ratio of sand to total aggregate should be increased somewhat and the proportion of aggregate to paste reduced. For certain members the larger sizes of the coarse aggregate should be eliminated. To design mixes for such conditions the *C-x* curve for the materials is not appreciably changed but new *C-c*, *S-x*, and *W-x* curves should be determined. Data for these can be determined by trial without performing strength tests. In Fig. 8 are shown such additional curves for a 7-in. slump, using the materials of the previous problem with coarse aggregate gradation unchanged.

To facilitate the use of this method, the slumps, sand ratios and moisture contents suggested by the Portland Cement Association in *Design and Control of Concrete Mixtures* are tabulated in Table 4.

TABLE 4.—USEFUL DATA FOR DESIGNING CONCRETE MIXES

RECOMMENDED SLUMPS FOR CONCRETE

Type of Structure	Slump—Inches	
	Minimum	Maximum
Massive sections, pavements and floors laid on ground	1	4
Heavy slabs, beams, or walls	3	6
Thin walls and columns, ordinary slabs or beams	4	8

RECOMMENDED PROPORTIONS OF AGGREGATES

Maximum Size of Coarse Aggregate, Inches	Ratio of Fine * to Total Aggregate on Basis of Dry, Compact Volumes, Measured Separately	
	Minimum	Maximum
$\frac{3}{8}$	0.55	0.70
$\frac{3}{4}$	0.40	0.60
1 and over	0.30	0.50

* The finer the sand, the lower will be the percentage required.

(*Table continued on next page*)

TABLE 4.—USEFUL DATA FOR DESIGNING CONCRETE MIXES (*Continued*)

APPROXIMATE AMOUNTS OF FREE WATER IN AGGREGATES[a]

Very wet sand	6 to 8 per cent by weight
Wet sand	4 per cent by weight
Moist sand	2 per cent by weight
Moist gravel or crushed stone	1½ per cent by weight

[a] The amount of free water carried increases with the fineness of the aggregate.

APPROXIMATE ABSORPTION OF AIR DRY AGGREGATES

Ordinary sand	0.5 to 1 per cent by weight
Gravel and crushed limestone	0.5 to 1.5 per cent by weight
Trap rock and granite	0.3 to 0.5 per cent by weight
Porous sandstone	7.0 per cent by weight

Since aggregates in air dry condition absorb water, allowance for absorption should be made when they are used in that condition. The absorption may be approximated by the method outlined in Art. 483. The values in Table 4 may be used in absence of test data.

On important work moisture determinations should be run several times a day. Simple methods are indicated in Art. 483. When moisture content determinations are not made, the approximate values in Table 4 may be assumed.

483. The Determination of Absorption and Moisture in Aggregates.— Since the moisture in the aggregates is of considerable importance in determining the amount of mixing water to add to a given mix, we digress to consider simple methods for determination.

Absorption of air-dry fine aggregate may be approximated * thus:

Weigh to nearest ½ gram a representative 3000-gram sample of sand. In all succeeding operations avoid loss of sand. Spread approximately two-thirds of the sample in a shallow pan 16 by 16 in., or larger, sprinkle with a small amount of water, and mix thoroughly. Allow some of the moistened sand to flow from a smooth tin scoop into pan. Observe whether it flows freely, or forms balls. If it flows freely, spray on more water; if it balls up, add some sand from the remainder of the original sample. When the moisture content has been raised until the sand is just on point of balling up as it flows from scoop, determine weight of moistened sand, also weight of residue of original 3000-gram sample. Calculate the percentage of moisture to the nearest 0.1 per cent. Repeat the determination at least once.

The absorption of the coarse aggregate may be determined as follows: Immerse a representative 100-gram sample in clear water at room temperature for 30 minutes. Then pour off the water and surface dry by rolling in a towel or clean cloth. Weigh sample after surface drying. Determine percentage of water absorbed to nearest 0.1 per cent.

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* See a more accurate method, A.S.T.M., Des. C 128–36T.

Moisture Content of an aggregate can be most accurately found by determining the loss in weight of a representative 1000-gram sample of sand, or a 2000-gram sample of coarse aggregate, after it has been dried to constant weight. Drying can be done over a hot plate, or by saturating the sand with alcohol and igniting. Since only the free, or surface, moisture is used in water-cement ratio calculations, this simple method must be followed by a determination of the absorption of the aggregate.

The free moisture can also be found from the differences in specific gravities of moist and surface dry sand as outlined in A.S.T.M. Des. C 70–30. A more serviceable device for field use developed by the Portland Cement Association is shown in *Proc. Am. Conc. Inst.*, Vol. 25, p. 266. In this connection also refer to A.S.T.M. Des. 128 and 127.

When the moisture in sand varies 1 or 2 per cent from batch to batch, the above methods requiring 20 to 30 min. per determination are slow and cumbersome. C. E. Wuerpel in construction of the Alton lock on the Mississippi River measured the electrical conductance of a portion of the sand in the measuring hopper (see *Engr. News-Rec.*, Vol. 115, p. 52). The method is based upon the principle that the conductance of a given volume of sand under a given degree of compaction increases with the moisture content. By making calibrations for the type of water used and for different temperatures in the sand he was able to determine rapidly average moisture contents to 0.3 per cent of the sand weight.

484. Proportions for Different Constructions.—The mixes listed below are satisfactory when good materials and workmanship are used. Proportions marked with an * refer to natural cement mortars. For ease in laying, the Portland cement (*C*) in masonry mortars is often tempered with 25 to 50 per cent of quicklime paste or hydrated lime (*L*). Compressive strength values are for moist curing at 70° F. Allowance for effects of other temperatures can be made from information in Art. 539. For influence of different curing conditions see Fig. 8 and Table 6, Ch. XIV.

Mortar for	Proportions by Volume
Laying masonry:	
In exposed or wet locations	1 : 2 to 1 : 3
In exterior walls of buildings	1*C* : 1*L* : 6*S* 1* : 2 to 1* : 3
Filling joints in sewer pipe	1 : 0 to 1 : 2 1* : 0 to 1* : 1
Surfaces of floors and sidewalks	1 : 1 to 1 : 2
Waterproof linings	1 : 0 to 1 : 2
Cement bricks and blocks	1 : 2½ to 1 : 4

(*Table continued on next page*)

	Desired Compressive Strength at 28 Days (Lb.-In.²)	Water-Cement Ratio		Proportions by Volume
		By Weight	Gallons per Sack	
Concrete for				
High early strength in pavements; strong columns, beams, and slabs; or for structures very severely exposed	5500	0.40	4½	1 : 1 : 2 to 1 : 1½ : 3
Walls, dams, piers, pavements, and other structures requiring high strength or watertightness; or for structures severely exposed	4500	0.50	5½	1 : 1½ : 2½ to 1 : 2 : 3½
Walls, dams, piers, reservoir linings, exposed to weather in northern climate. Watertight structures, pipes, tanks, sewers, pavements, and thin members exposed to frost action	3800	0.55	6	1 : 1½ : 3 to 1 : 2¼ : 4
Walls, dams, piers, reservoir linings, exposed to weather in southern climate. Basement walls or thin structural parts subjected to moderate exposure	3000	0.60	6¾	1 : 2 : 3 to 1 : 2½ : 4
Enclosed structural members, piers, retaining walls, foundations, and footings protected from alternate wetting and drying and from severe weather	2200	0.65	7½	1 : 2¼ : 3½ to 1 : 3 : 5
Mass concrete requiring little strength and well protected	1800	0.75	8½	1 : 2½ : 4½ to 1 : 3½ : 6

485. Testing the Quality of Concrete.—Auxiliary tests on the aggregate are of assistance in making a selection of the proper aggregate, and the use of proper methods of proportioning tends toward economy in cement, but the value of these tests and schemes can only be ascertained by tests on the concrete itself. In making such tests, the sampling and proportioning of the materials, the method of mixing, the placing and the curing conditions for the specimens should all be controlled so that the test-pieces will in every way represent the concrete to be used in construction. Workability tests and strength tests are the chief control tests made on concrete.

Workability is usually measured by the slump or the flow of a conical frustum of fresh concrete. To make the slump, or consistency, test (see A.S.T.M. *Standards*), a frustum with top diameter 4 in., bottom diameter 8 in., and altitude 12 in. is placed on a metal base and filled with fresh concrete in three equal layers. As each layer is placed, it is puddled 25 strokes with a bullet-pointed rod. The surplus concrete is struck off, the mold slowly withdrawn vertically, and the subsidence or slump of the top of the mass is measured. The flow test is described in App. A.

For testing the compressive strength of concrete a cylinder with ratio of diameter to height of 1 : 2 is good practice (see Art. 113). The diameter of the mold should be at least three times and preferably four times the maximum diameter of the aggregate. With aggregate between $\frac{3}{4}$ in. and 2 in. in maximum diameter, a 6×12-in. cylinder is generally used. For tests of concrete with larger sizes of aggregate 8×16 and 10×20-in. cylinders are used. Standard methods for making and testing compression specimens are given in A.S.T.M. *Standards* (see also App. A.).

Transverse tests of concrete afford a good means of determining quality, especially in concrete pavement construction. By use of the modified cube test, Art. 113, the compressive strength can also be obtained from the beam ends. Methods of mixing, molding, curing, and testing are given in A.S.T.M. *Standards*, Des. C 78-38. It is essential that non-absorbent molds be used. Beams should be molded in two equal layers. Each layer should be puddled with a $\frac{5}{8}$-in. rod, 25 strokes per square foot of top surface. The sides of each layer should be surfaced with a mason's trowel. The top of a beam should be struck off flush with the top of the mold with a trowel. Evaporation of moisture from the top surface should be prevented by placing the beam in a moist closet or by covering the top with a wet canvas until the molds are stripped. For concrete made with aggregate having maximum diameter of $\frac{3}{4}$ to $1\frac{1}{2}$ in., a beam 4×6 in. in cross-section can be used; for concrete of aggregate under 2 in. in size, a beam 6×6 or 6×8-in. in cross-section is satisfactory. The span length for the beam should not be less than twice and preferably not less than three times the depth of the beam.

Loading beams at the third points of the span produces a wider distribution of the maximum fiber stress than a center loading or a cantilever loading. For third point loading, the length of span is immaterial * when the length is over twice the depth, but for the center loading and especially the cantilever loadings the effect of span length is noticeable. The cantilever loading gives the highest modulus of rupture and the third-point loading the lowest. The discrepancy for short spans may amount to 30 per cent. Hence it is necessary to specify the method of loading for transverse tests on concrete. A suitable machine for field testing is described in Art. 52. Owing to the presence of more or less shrinkage strains in the top surfaces, it is well to subject top fibers to tensile stress in making beam tests. The relation of modulus of rupture from beam tests to the tensile and compressive strength of concrete is considered in Art. 513.

When using either strength test as a criterion of quality, there should be made at least three specimens for each variable covered. For high-early-strength concrete, tests at 1, 2 or 3 days are made, but for ordinary mixes 7 and 28 days are the more common test ages. In some road constructions, beam tests are run at frequent intervals in order to determine the proper time for opening the road to traffic. When the durability of concrete is in question or the effect of curing is to be ascertained, tests should run over much longer periods of time.

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* See Report of Research Director of Portland Cement Association, 1928.

For certain purposes, abrasion, absorption, fire or freezing tests of concrete are made (see Ch. VIII and XIV for types of tests used.)

486. Quantities of Materials Required for One Cubic Yard of Mortar and Concrete.—The values given in Table 5 are computed from the results of yield tests on 15 different sands and screenings.* All of these aggregates were in air-dry condition at the time of test. It will be appreciated that the values will not apply to all mixes with equal accuracy, since the kind of cement, per cent moisture in aggregate, gradation of sizes, and percentage of particles passing a No. 100 sieve will considerably influence the yield. The greatest variations in yield are produced by variations in the moisture content in the aggregate. If the per cent moisture is known allowance for such variations may be made by using the information in Fig. 5 in connection with the yields in Table 5.

TABLE 5.—YIELD IN MORTAR FOR DIFFERENT PROPORTIONS OF VARIOUS AGGREGATES BASED ON LOOSE MEASUREMENTS OF VOLUME *

All aggregates passed a ¼-in. sieve and were air dry. Plastic consistency

No.†	Per Cent Voids	Per Cent (by Wt.) Passing Sieve				Yield for Mix			
		10	30	50	100	1 : 2	1 : 3	1 : 4	1 : 5
S ‡	37.0	100.0	0	0	0	1.18	1.11	1.08	1.07
Sd1	36.5	86.4	39.0	9.1	2.8	1.18	1.08	1.03	1.01
Sd2	35.2	81.2	61.4	34.5	9.7	1.25	1.15	1.10	1.07
Sd3	38.2	91.9	39.7	13.7	1.2	1.22	1.11	1.06	1.03
Sd4	39.8	100.0	95.8	62.5	8.6	1.30	1.15	1.09	1.04
Sd5	45.3	100.0	99.8	67.6	5.7	1.22	1.09	1.03	0.99
Sd7	36.6	67.7	25.9	11.2	2.2	1.19	1.07	0.99	0.95
Sd8	36.4	82.0	55.3	16.1	1.9	1.21	1.09	1.95	1.01
Sd9	36.0	66.8	13.9	4.9	1.4	1.14	1.03	0.98	0.95
Sd10	27.9	69.7	34.0	17.4	6.5	1.26	1.14	1.05	0.96
Sd11	35.0	72.0	23.8	4.3	0.5	1.21	1.08	1.01	0.99
Sg1	42.0	62.8	35.5	25.1	13.0	1.13	1.01	0.93	0.88
Sg3	39.0	64.0	28.0	19.5	13.8	1.15	0.99	0.92	0.88
Sg4	40.0	69.0	32.6	23.8	15.9	1.15	1.01	0.93	0.88
Tg1	43.6	34.6	15.4	11.5	7.5	1.07	0.97	0.89	0.84

* Weight per cubic foot of cement was taken at 100 lb.
† Sd = sand; sg = screenings; Tg = zinc mine tailings. ‡ Standard Ottawa sand.

For common mixes and aggregates the volume of concrete can be very closely estimated from the sum of the absolute volumes of the dry materials and the water. With lean mixes and also with porous aggregates such estimates will be smaller than the actual volumes of concrete. The following statements of this principle are useful:

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* *Proc. A.S.T.M.*, Vol. 13, p. 834.

$$S=\frac{27}{0.5+x'+\dfrac{W_s}{62.5\,K_s}+\dfrac{W_g}{62.5\,K_g}}\quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

$$S=\frac{27}{0.5+x'+s(1-v_s)+g(1-v_g)}.\quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

Here S = the number of sacks of cement per cu. yd. of concrete;
x' = the volume of water in cu. ft. per sack of cement;
W_s = pounds of surface-dry fine aggregate per sack of cement;
W_g = pounds of surface-dry coarse aggregate per sack of cement;
K_s and K_g = apparent specific gravities of fine and coarse aggregates, respectively;
s = number of volumes of fine aggregate per sack of cement;
g = number of volumes of coarse aggregate per sack of cement;
v_s and v_g = voids in fine and coarse aggregate, respectively, as measured on job.

In using either of these rules the excess moisture in the aggregates should be included in computing x'.

Example: Calculate the materials required for 200 cu. yd. of 1 : 2 : 3 (by vol.) concrete. The water-cement ratio is 6 gal. per sack of cement. The sand contains 3 per cent and the gravel 1 per cent of excess water. The weights per cu. ft. measured loose at the job are sand 95 and gravel 102 lb. Apparent specific gravities are sand 2.65 and gravel 2.70.

By formula (1): $x' = 6 \div 7.5 = 0.8$, $W_s = 2(95 \div 1.03) = 185$ lb., and $W_g = 3(102 \div 1.01) = 303$ lb., hence

$$S = \frac{27}{0.5 + 0.8 + 185 \div (62.5 \times 2.65) + 303 \div (62.5 \times 2.70)} = 6.41 \text{ sacks}$$

Sand, moisture included, per cu. yd. of concrete $= 6.41 \times 2 \times 95 = 1215$ lb. Gravel, moisture included, per cu. yd. of concrete $= 6.41 \times 3 \times 102 = 1960$ lb. Water to be added per cu. yd. $= 6.41 \times 0.8 \times 62.5 - 1215 \times \dfrac{.03}{1.03} - 1960 \times \dfrac{.01}{1.01} = 265$ lb.

By formula (2): the voids may be measured, or from data above,

$$1 - v_s = \frac{95 \div 1.03}{62.5 \times 2.65} = 0.557 \text{ and } 1 - v_g = \frac{102 \div 1.01}{62.5 \times 2.70} = 0.599,$$

hence
$$S = \frac{27}{0.5 + 0.8 + 2 \times 0.557 + 3 \times 0.599} = 6.41 \text{ sacks.}$$

If purchased on a surface-dry basis there would be required for 1 cu. yd. of concrete 0.59 ton of sand and 0.97 ton of gravel. If sold damp and loose by the cubic yard the sand required is 1215 ÷ (27 × 95 = 0.48 cu. yd., and the gravel is 1960 ÷ (27 × 102) = 0.71 cu. yd. Values of specific gravity for common aggregates may be found in Art. 471 and 268. Errors of 0.1 in the assumed value will not greatly affect the computed quantities. Voids may be readily computed by entering Fig. 6, Art. 471, with weight of surface dry sand in a cubic foot and apparent specific gravity.

487. Interpretation of the Meaning of Proportions.—Sometimes it becomes necessary to substitute a pit-run gravel or other mixed aggregate when the specifications call for separate measurement of the fine and coarse aggregate. Since such substitution often causes disagreement, it should be provided for in the specifications. To illustrate, consider a 1 : 2 : 4 mix of cement, sand and gravel measured by volume. It has been erroneously argued many times that the equivalent proportions with pit-run gravel are 1 : 6, whereas volume measurements of 2 : 4 mixture of sand and gravel will generally show that about 1 : 5 or even a richer proportion is the proper equivalent. Furthermore, unless the pit-run material is well graded, it is likely that the quality of the substituted mix will be inferior to the specified even though the equivalent ratio of cement to aggregate is used.

MIXING, PLACING, AND CURING

488. Principles of Proper Mixing.—The first consideration in mixing either mortar or concrete should be to bring all materials into a homogeneous mixture of uniform consistency in the minimum amount of time and without waste. Whatever method of mixing is used, in order to insure that in the completed batch each grain of aggregate will be coated with cement paste, the aggregate and cement should be dry mixed for a short time. The object of this dry mixing is to distribute evenly the cement throughout the mass and to prevent it from balling-up when the water is added. Since the time of mixing may be somewhat shortened if dry sand is employed, it may be economical on large jobs to cover the storage pile. On the other hand, a porous aggregate should not be allowed to completely dry since it will absorb water from the cement paste and adversely affect the hardening properties of the mix. Instances in which this action has caused a failure of the structure have been recorded.

The question of the proper consistency is largely dependent upon the character of the work. At the present time variations from a dry consistency which will barely show moisture under heavy ramming to a soupy mix which can be spouted into the molds are in use. The general practice in this country is to employ a wet mix which will readily flow for nearly all reinforced concrete construction. In European countries practice favors a somewhat drier consistency. The effects of different consistencies on the properties of mortar and concrete are discussed in Art. 503, 511 and 527.

489. Hand Mixing.—Mortar can be hand mixed most satisfactorily in a tight wooden or sheet-metal box. For a 3- or 4-wheelbarrow batch a box 4×8 ft. with sides 8 or 10 in. high is convenient. The sand is spread in a layer of uniform thickness over the bottom of the box and covered by a similar layer of cement, or if the batch is large the cement may be sandwiched between equal layers of sand. The dry materials are then thoroughly mixed by hoe or by shovel until the mass is of uniform appearance.

If shovels are employed the men should work in pairs, partners facing each other on opposite sides of the box. Beginning at one end and working toward the other, both men shovel simultaneously into the pile giving each shovelful a flip which scatters the material as it falls. The entire pile should be given at least three turns in this manner. A long crater is next formed in the pile and filled with water. The batch should then be given at least three more turns with the shovels.

Mixing by hoe is not so effective as by shovels, if two or more men are available. If the hoe is employed, water is generally added at the end of the box, the dry mix is rapidly drawn down into it, and the whole mass vigorously worked until the consistency is uniform.

For hand mixing of concrete, a tight platform somewhat larger than the mortar box is desirable, and the mixing should be done with shovels. The following method is rapid and conserves labor. The sand is spread in a layer 4 to 6 inches thick at one end of the platform and covered with the proper proportion of cement. These materials are then given three turns and the mixture formed into a wide crater into which the stone or gravel is dumped. The predetermined amount of water is then poured over the gravel and the edges of the pile gradually turned in to absorb the water. The whole mass is then given three or more turns until it is of uniform consistency.

For mixing small batches of 3 to 5 6×12-in. test cylinders, a 3½×5-ft. tray of No. 16 gage galvanized iron with its edges rolled upward about 3 inches is convenient. The procedure for mixing outlined above is satisfactory, but the dry sand and cement should be mixed at least six turns and the wetted batch ten turns.

490. Machine Mixing.—Most concrete is now mixed by machine. Although there are a great many designs and forms of mixers, they may all be separated into two classes—batch mixers and continuous mixers. In the operation of a batch mixer a definite charge of materials is mixed and discharged before another batch is admitted. The other type of mixer receives and discharges material continuously.

In general, concrete made in a batch mixer is more uniform than the product of the continuous mixer for the following reasons: All portions of the charge are mixed together in the batch machine, whereas in the continuous mixer product the uniformity of successive portions depends upon the regularity of the feeding device. Furthermore, in most types of continuous mixer the time of mixing is too short for thorough work, whereas in the batch machine the mixing period can be regulated as desired.

In selecting a mixer, special attention should be given not only to the initial cost of the machine but also to other factors which vitally affect the quality of the product, efficiency, cost of operation and maintenance, such as: 1, time required to produce a homogeneous mix; 2, waste in charging and discharging; 3, rapidity of charging and discharging; 4, ease in cleaning; 5, durability of mechanical parts; 6, capacity of the power drive; 7, visibility of charge during mixing; 8, accuracy of water-feeding device; 9, uniformity in quality of discharge; 10, completeness of the discharge. In general the capacity of a batch mixer should be a little greater than can be handled by the gang employed.

In mixing with batch mixers it is desirable to have the sand, cement, and coarse aggregate intermingle as much as possible as they are gradually chuted into the mixer in order to cut down time in the mixer. A small amount of water should precede the dry materials, and then it should be continuously admitted in such manner that the blades and drum are washed and the water is well distributed through the mass. Usually admission of water is continued until after all other materials are in the drum. Experiments with small mixers on wet concrete have shown that the 28-day compressive strength of the concrete is improved from 5 to 15 per cent by increasing the time of mixing from 30 sec. to 10 min., but the gain in strength after mixing 5 min. was small. Premixing of the cement and water does not affect an increase in strength. For producing uniform and impervious concrete, mixes cured only a few days require more mixing than those cured a month; lean mixes require longer mixing than rich mixes; dry mixes require longer periods than wet mixes; and mixes with fine sand require more time than those with coarse sand.

For mixers of 1, 3, and 5 cu. yd. capacity, the Bureau of Public Roads tests * indicate that there is no material gain in strength obtained by extending the time of mixing concrete of 1 to 6-in. slump beyond one minute. They indicate also that with the largest mixers there is a considerable addition of fine material owing to attrition as the mixing period is increased from 1 to 4 min. At the Grand Coulee Dam † the total time required for mixing was 3 min. (with ¾ of a min. allowed for charging and discharging the 4 cu. yd. mixers.)

In cities of 50,000 inhabitants or over, ready-mixed concrete is now being sold. This commodity is produced either (*a*) by a central mixing plant and hauled to job by trucks equipped with agitators or (*b*) by a central proportioning plant and a transit mixer which operates during conveyance to the job. Tests by S. C. Hollister ‡ indicate that there is little effect on compressive strength due to variations in time of transit mixing from 40 turns of the drum up to a period of 90 min. The concrete in Hollister's tests had 5 sacks of cement per cu. yd. and varied from 1 to 7 in. in slump. Since the slump decreased markedly during the longer periods of mix, it is evident that workability is the principal limitation on time of mixing in such operation.

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* *Public Roads*, July, 1928, and November, 1934.

† *Engr. News-Rec.*, Jan. 23, 1936, p. 119.

‡ *Proc. Am. Conc. Inst.*, Vol. 28, 1932, p. 405.

If full advantage is to be taken of the properties of drier mixes which now can be so effectively placed by vibration, either longer time must be allowed in mixing such batches with present mixers, or special mixers must be designed to handle the drier concrete.

491. A Comparison between Machine- and Hand-mixed Concretes.—If a sufficient number of turns is employed, concrete can be as well mixed by hand as by machine. However, the cost of such thorough work prohibits its use in practice. With the practiced methods of hand mixing it is not possible to secure so homogeneous mixtures as with machine mixing. This non-homogeneity of the hand-mixed material is especially noticeable when the permeability of the concrete is tested.

In a series of tests at the University of Wisconsin on forty-eight 10- by 24-in. cylinders of concrete, made in proportions varying from 1 : 1 : 2 to 1 : 4 : 8, by volume, with crushed limestone coarse aggregate, the relative strengths of hand- and machine-mixed concretes were determined. In making the hand-mixed specimens the cement and sand were turned twice dry; the cement, sand, and stone, twice dry; the whole mass was then wetted and given three more turns. The machine-mixed concrete was turned for one minute dry and two minutes wet in a No. 0 Smith batch mixer running at 26 r.p.m. In order to obtain a medium consistency, the machine mixes required an average of 9.2 per cent water and the hand mixes took an average of 9.9 per cent water, by weight of dry materials.

As a result of the extra water and lack of mixing in the hand mixes, the average ratios of the strengths of specimens of machine-mixed concrete to the strengths of the hand-mixed averaged as follows: 1 : 1 : 2 mix, 1.38; 1 : 2 : 4 mix, 1.25; 1 : 3 : 6 mix, 1.33; and 1 : 4 : 8 mix, 1.07.

492. Handling of Concrete.—From the standpoint of securing good concrete after placement, certain fundamental principles should be borne in mind in handling the concrete.

For conveying concrete, wheelbarrows and two-wheel carts are commonly employed on small jobs, whereas elevators with gravity chutes, cars, belt conveyors, and cableways are used on large structures. For lining tunnels, concrete is often transported by compressed air. In using wheelbarrows or carts, attention should be given to minimizing the length of haul not only for the sake of economy in labor but also to prevent separation of the ingredients in the wheelbarrow due to jarring. The spouting of concrete by gravity requires a very wet, soupy mixture, unless a high pitch is employed; consequently the strength and density of the product suffer when this method is used. Whatever system is employed, the number of changes from one conveying vessel to another should be minimized in order to avoid waste of mortar due to slopping.

At a power cost approximating 1 cent per cu. yd., concrete of 2- to 6-in. slump can be pumped through 6- or 8-in. pipes for horizontal distances up to 1000 ft. by Pumpcrete machines. The latter are built to deliver up to 65 cu. yd. per hr.

For placing concrete under water, some method must be used which prohibits the separation of the cement or mortar from the stone. This is sure to occur if the concrete is poured into open water; the stone, sand, and cement will be found in layers one above the other in the order named. Wherever possible the work should be enclosed in a coffer-dam to avoid wave action and prevent currents about the structure. Enclosed buckets holding $\frac{1}{2}$ cu. yd. or more, which can be lowered to the bottom and emptied without the contents being subjected to the wash of the water, have been successfully used to deposit concrete in depths of 200 ft. In this method a dry consistency is employed and care is taken to create as little disturbance as possible in raising and lowering the bucket.

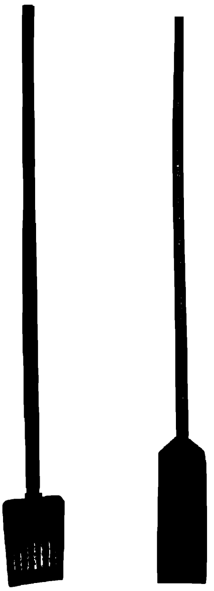

Fig. 9.—Facing and Tamping Irons. (*a*) Gridiron tamper for facing side walls. (*b*) Flat-faced tamper. (*c*) Grid tamper for floors or walks.

A tremie, or pipe with a flared top and of sufficient length to reach bottom, is often used to deposit concrete under water. Commonly a battery of tremies is effectively centered over the work. Then each tremie is kept filled with concrete as it is gradually raised.

In the construction of foundations for the San Francisco-Oakland Bay Bridge, concrete with 6 sacks of cement per cu. yd., 50 per cent of the aggregate sand, and a water-cement ratio of 0.85, by volume, was used. At one month the compressive strengths of cores cut from this sub-aqueous concrete averaged 3562 to 3954 lb./in.^{2}. (See *Proc. Am. Conc. Inst.*, Vol. 33, p. 346-1.)

493. Placement of Mortar and Concrete.—Mixtures of dry consistency should be placed in layers not over 8 in. thick. Wet concrete can be placed in much thicker layers depending upon the consistency and width of the cross-section. Dry concrete should not be allowed to fall more than a few feet, since the coarse aggregate is likely to become separated from the mortar. When concrete must be poured from a considerable height, it is desirable to use an inclined chute both to avoid separation of ingredients and to avoid excessive pressure on forms.*

In placing concrete of 2- to 6-in. slump, use of the spading and facing tools shown in Fig. 9 will improve the appearance of vertical surfaces. For placing concrete of 1-in. slump or less in sidewalks or floors, the grid tamper is useful. Pockets in thin walls and columns can be avoided by puddling a wet mix with long rods.

Vibrators.—The internal, electrically driven vibrators, Fig. 10, are effective devices for uniformly consolidating concrete in walls, columns, beams, or other units. External vibrators are usually applied to horizontal surfaces like floors or pavements or to the compaction of concrete products in molds. Pavement slabs have been successfully compacted by vibrating a cylindrical tube supported by and in front of the finishing machine in the roll of concrete formed at the strike-off device. Vibration of forms or of reinforcing has not met with favor in this country.

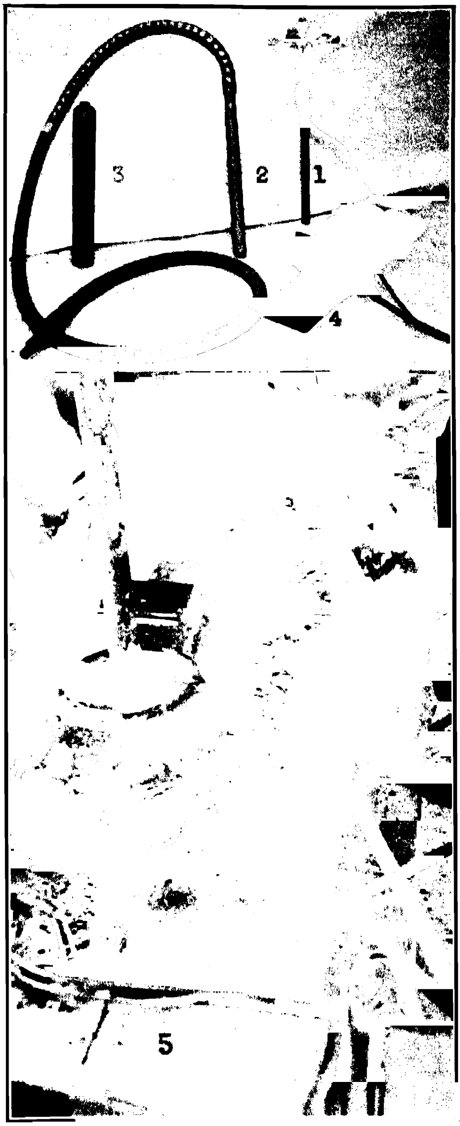

Fig. 10.—Types of Vibrators. Sizes: (1) 1⅛ by 21 in., (2) 1⅞ by 18 in. (with flexible shaft), (3) 2¼ by 20 in., (5) 6½ by 18½-in. wt. 96 lb. (2 men required). (4) External Vibrator, ½ H.P. motor. Speeds (1) 12,000 r.p.m.; others 3500 to 5000 r.p.m.

In most of the vibrators a displacement of 0.03 to 0.09 in. from mean position is caused by revolving an eccentric weight at a speed in excess of 3500 r.p.m. Using an internal vibrator with a spud $2\frac{3}{4}$ in. in diameter, weighing 24 lb., running at 6000 r.p.m., and an eccentric moment of 2.3 in-lb., it is possible to consolidate concrete of 0-slump into a plastic mass within a radius of 12 in. of the vibrator in 20 to 30 sec. With concrete of $\frac{1}{2}$-in. slump the time requirement is about one half. The energy required to consolidate 0-slump concrete is approximately 1500 to 3000 ft.-lb. per cu ft.; for $\frac{1}{2}$-in. slump, the energy required is one fourth as much.

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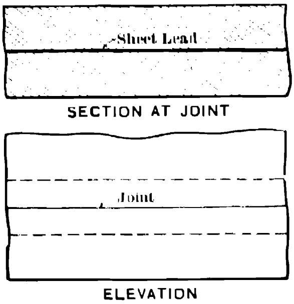
* See discussion in *Engr. Record*, Vol. 59, p. 279.

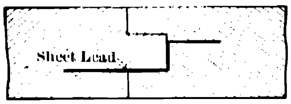
Vibrators are most effectively used on relatively dry mixes, preferably with slumps less than 2 in. Their use makes it possible to reduce sand contents down to 28 to 35 per cent of the total aggregate weight and to place more harshly graded mixes than with hand methods.*

Strong concrete and early form removal have been attained in certain house constructions by applying a partial vacuum to a wet concrete after placement. Thus the fluidity of the concrete is effectively used in placing; then the excess water, harmful in hardening, is removed before setting occurs. (See *Proc. Am. Conc. Inst.*, Vol. 34, p. 305.)

In sidewalk and floor construction it is best to roughen and clean the base before it has hardened and apply the topping immediately. Committee 802 of the A.C.I. recommended the following topping. Make a mix of 1 part cement, 1 part coarse sand with not more than 10 per cent passing a No. 50 sieve, and $1\frac{1}{2}$ to 2 parts of gravel or crushed stone ranging from $\frac{1}{4}$ to $\frac{3}{8}$ in. in size. Use $4\frac{1}{2}$ to 5 gal. of water per sack of cement, a 2-min. mixing period, and a consistency as dry as can be screeded. If necessary, a small change can be made in the coarse aggregate proportion. After this topping mixture has been screeded to proper level, it should be floated with a wood float until a small amount of mortar is brought to the surface for finishing purposes. Then it should stand for 30 to 45 min. to prevent an excess of fine particles coming to the surface when it is troweled. Steel troweling should then be done until the surface is smooth and free from defects.



(a) JOINT HORIZONTAL



(b) JOINT VERTICAL

FIG. 11.—Methods of Making Water-tight Joints.

The Cement Gun.—An apparatus which is being considerably used for applying a coat of mortar or grout to large surfaces is the cement gun. The essential feature of this machine is a vertical tank into which the mixture of sand and cement is admitted through a bell hopper. At the lower end of the tank is placed a horizontal wheel which is provided with radial arms to sweep the dry mortar under an outlet pipe. The dry mortar is driven out of the tank by means of air pressure which also serves to operate an air motor that turns the distributing wheel. From the outlet the mix is driven through a flexible hose, which may be of any length up to 200 ft., to a nozzle. As the mixture is shot through the latter it is tempered with sufficient water to produce a plastic mortar and is then deposited at high velocity in the form of a spray on the surface of the work. For mobility the machine is mounted on a truck.

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* See *Proc. Am. Conc. Inst.*, Vol. 31, pp. 527–551; Vol. 32, p. 445. See also *Proc. Highway Res. Board*, Vol 15, p. 217; Vol. 16 p. 193; Vol. 17, pp. 279–327.

In 1936 tests on 1 : 3, 1 : 4, and 1 : 5 mortars placed in fifty-three 3- by 3- by 28-in. prisms by a cement gun were made for a thesis by R. D. Culbertson and L. J. Deno at the University of Wisconsin. Their data show that there was little difference in the average strengths of these mixes after placement by the gun. After 7 days damp curing and 21 days in the air of the laboratory, the moduli of rupture of individual specimens of gunite ranged from 629 to 1030 lb./in.^{2}, and the compressive strength (modified cube method) ranged from 4750 to 11,110 lb./in.^{2}. Other tests show such mortars have high density. (*Concrete*, Vol. 9, p. 26). The cement gun has been used for facing dams, for reinforcing old sewers, for placing a protective coating of mortar around structural steel in buildings and tunnels, for lining tunnels, and for repairing the walls of furnaces and coke ovens.

494. Joining Old and New Work.—Whenever water-tight concrete is desired, pouring should be carried on continuously * or a water-tight joint † must be provided (see Fig. 11). On less important structures the surface of the old work should be roughened thoroughly, cleaned of all laitance and dirt with wire brushes, saturated with water, and then allowed to dry until the surface will absorb water from the fresh mortar or concrete. For roughening the surface of old work, dilute hydrochloric acid is effective, but it should be entirely washed off before bonding.

A vibrator is a valuable aid in bonding fresh concrete or mortar to old work. In 1936 at the University of Wisconsin a series of 428 flexural tests on 6- by 6-in. beams tested over a 16-in. span were made by J. E. Liebmann and R. E. Stiemke to determine the bond of fresh concrete to hardened concrete (*Proc. Highway Research Board*, Vol. 16, p. 193). Included variables in these tests were 3 water-cement ratios, 3 slumps, both high-early-strength and Portland cement, vertical and horizontal joints, two ages at bonding and two ages of bonding, vibration, and hand placement, and condition of the surface.

All specimens were cast in tight forms and moist-cured until tested. Surfaces to be bonded were cast against clean plywood. In bonding specimens with vertical joints, an external vibrator was used for 10 sec. or less per specimen; for bonding on horizontal joints a 1¾-in. internal vibrator was used for 15 to 20 sec. per specimen. Beams were made with two joints 9 in. apart and tested with a joint under a center load over a 16-in. span. Reported bond values are computed moduli of rupture.

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* Examples in erecting stand pipes, *Concrete Cement Age*, December, 1913; February, 1914.

† For examples of joints, see Rept. of Com. E-8, *Proc. A.C.I.*, Vols. 24 and 25.

The following are some of the more important conclusions obtained from these tests. Brushing or grouting of the hardened surfaces had no appreciable effect on the bond of the high-strength concrete of 0.47 *w/c*, by weight. Allowing the surfaces to be bonded to dry for 3 days in the laboratory air effected a 15 to 25 per cent increase in bond over that obtained when surfaces were dried 1 day. Ageing 2 days or 28 days prior to bonding produced no effect on the 28-day bond strength. Changes in consistency from 0- to 6-in. slump affected the bond strength little, if the water-cement ratio was constant. The 28-day bond strength of high-early-strength concrete was 10 to 20 per cent higher and more uniform than that developed by Portland cement concrete. The bond of the latter increased approximately 30 per cent between 7 and 28 days.

For concrete of 0.47 *w/c* the bond modulus of rupture in a series of 108 tests averaged over 500 lb./in.^{2}, with a minimum of 338 lb./in.^{2}. The average ratio of bond to normal modulus for this series of tests was 0.67. Figure 12 shows the effect of the water-cement ratio on bond and also the superiority of the bond at the top fibers in vertical joints. With horizontal joints there was less range in bond, although the average bond was about the same as in vertical joints. With cement content constant, the bond obtained with vibration was over 40 per cent greater than that obtained by hand puddling.

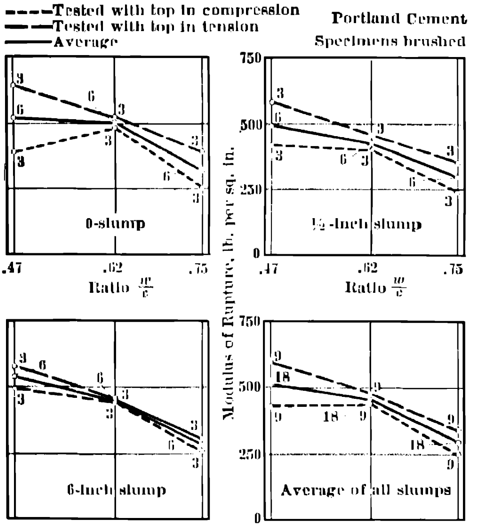

FIG. 12.—The Effect on Bond of Position of Beam in Testing.

495. Forms.—To prevent leakage of water and a loss of fine mortar, the forms should be made as rigid and nearly water-tight as possible. This feature should be given very careful attention when thin, water-tight sections are being constructed. If smooth surfaces are desired, plywood or tongued and grooved lumber planed on one side should be used. Oiling the forms diminishes warping and shrinkage and reduces labor in removing them. Collapsible steel molds or wooden forms covered with galvanized iron are economical for repeated use.

The pressure of unset concrete against forms depends on the depth of fresh concrete, the consistency and richness of the mix, the rate of pouring, the temperature, and the method of compacting in the forms. The tests reported by F. R. Shunk in 1908 (*Engr. News*, Vol. 62, p. 288) have been widely publicised, but tests by H. G. Roby (*Civil Engr.*, Vol. 5, p. 163, March, 1935) indicate that Shunk's values are much too large for certain conditions.

Roby made his tests by accurately measuring the deflection of a calibrated steel plate 6 in. wide and $\frac{7}{16}$ in. thick, supported on knife edges 28 in. apart. This plate was placed at the bottom of a form 2 ft. 6 in. square by 15 ft. high. The aggregates were sand and gravel of good quality. Mixing was done in a small batch mixer and the concrete was placed in 1-ft. layers with the ordinary amount of puddling and spading. Thirty-one complete tests were made. Three mix proportions 1 : 2 : 3½, normal, 1 : 1¼ : 2¼, rich, and 1 : 2½ : 5, lean, were used, each with a 7-in. slump; also a normal mix with a 3-in. slump was included. The effect of temperature and rate of placing on the maximum form pressure for the normal, 1 : 2 : 3½ mix, as determined by Roby are shown in Fig. 13. For the rich mix, the maximum pressure at a pouring rate of 4 ft. per hr. and a temperature of 60 to 70° F. was 1000 lb./ft.^{2}, or 42 per cent more than for the normal mix. The lean mix under similar conditions developed pressures 10 to 15 per cent less than the normal mix, and the dry mix 20 to 25 per cent less.

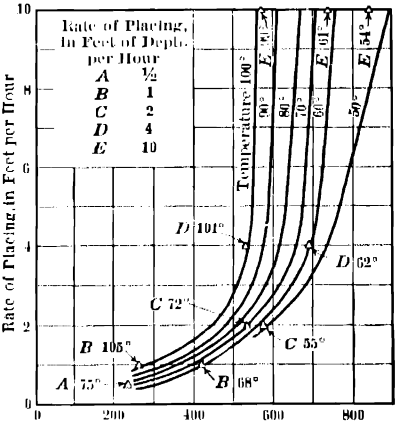

FIG. 13.—Relation of Pressure Exerted by Fluid Concrete on Forms to Rate of Filling. (H. G. Roby, *Civil Engineering*, Vol. 5, p. 163.)

When vibration is used to compact a dry mix, the pressures on the forms will reach a fluid intensity of 150 lb./ft.^{2}, if the rate of placement is rapid. Two tests by T. E. Stanton (*Concrete*, January, 1937, p. 5) indicate that vibrated concrete of 2-in. slump will maintain such pressure up to heights of 4 to 7 ft.

The time at which forms may be removed is dependent upon the rate of hardening of the cement and the temperature of the air. The best index of the proper time for removal of forms is afforded by a series of tests on small beams or cubes made and cured under the same conditions as the structure. Forms should never be removed until the concrete will support 150 per cent of its working unit stress. In warm weather, wall forms not over 10 ft. high can be removed in two or three days, but in the spring and fall when the temperature at night drops to 30° or 40° F., four to seven days should be allowed (see also Art. 539).

496. Shrinkage in Setting.—Owing to the shrinkage which takes place when concrete sets in air, see Art. 357 and 522, and the volume changes which occur due to variations in temperature, provision for contraction and expansion joints should be made.

In two-course sidewalks it is good practice to make joints $\frac{1}{16}$ to $\frac{1}{8}$ in. wide, every 4 to 6 ft. Such joints should extend through both surface coat and base. In concrete pavement constructions and in unreinforced walls, joints are placed from 30 to 50 ft. apart.* The width of the joint now used is quite variable depending upon the type of construction, position of joint, thickness of concrete, and conditions surrounding the construction. The width of joint varies from a plane of separation for contraction to a half inch or more for expansion. In thin members where the moisture changes are felt throughout the mass, wider joints will be more necessary than in thick sections. Expansion joints are commonly filled with a poured bituminous mastic or prepared felt and are provided with dowels to maintain alignment. In many cases construction joints are sealed with metallic plates to prevent the entrance of debris.

The tongued and grooved joint shown in Fig. 11 is impervious and also serves to preserve alignment when used in a vertical wall. A strip of sheet lead, bent as shown, permits free articulation of the joint. Provision for such joints should be made at all angles in order to avoid cracks due to settlement, contraction or expansion.

497. Curing.—No part of the process of making good mortar or concrete is more important than thorough curing. It is also one of the operations most frequently neglected. Dusty floors, loose surface coats on sidewalks and pavements, weak concrete blocks, leaky conduits and pipes illustrate defects frequently caused by improper curing. The effects of premature drying on the strength and permeability of concrete are discussed in Art. 529.

In warm weather the essential principle is to keep the work damp for a period of one to two weeks subsequent to pouring. Rich mixes do not require so long time for curing as lean mixes and are less affected by premature drying. Wet mixes suffer less than those of dry consistency when improperly cured. If provision cannot be made for wetting the work, the forms should be left on long enough to insure proper curing.

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* See Specifications for Concrete Roads, Streets and Alleys adopted by Second National Conference on Concrete Road Building.

The following methods of curing yield good results: sprinkling two or three times a day when not exposed to the sun, covering with burlap saturated twice a day, covering with a 2-in. layer of damp sand, earth, or sawdust wetted once a day, impounding a shallow pool of water over the surface of the work. Of these methods, the wet sand treatment is very effective for pavements and floors over a wide range of conditions. In arid regions where water for curing is difficult to obtain the Bureau of Reclamation has found that 2 coats of asphalt emulsion or coal tar cutback applied to the surface of the concrete within an hour after finishing are effective in retaining sufficient water for curing purposes.

Concrete blocks, brick, and tile can be given 70 per cent of their normal 28-day strength by subjecting them to properly controlled wet steam curing at temperatures of 125° F. for 15 hr. Menzel's tests (*Proc. Am. Conc. Inst.*, Vol. 32, p. 51) indicate that by curing in saturated steam at 350° F. (120 lb. per sq. in.) the full 28-day moist-cured strength of concrete units can be made available in 24 hr. He found that steaming was most efficient if begun 5 to 8 hr. after molding and continued for 8 hr.

498. Protection against Freezing.—In cold weather concrete should be protected from freezing until it has secured hard set. The effects of freezing on the properties of cements, mortars, and concretes are discussed in Arts. 359, 539, and 541. Some of the ways of preventing freezing will be briefly considered.

Tests on small 8-in. walls poured in 2-in. plank forms at a temperature of 10° F. have shown that concrete will set before freezing begins provided the temperature of the concrete is above 70° F. when it is poured. This temperature may generally be maintained by heating the mixing water alone. If necessary, the aggregates may be heated by building fires in large iron pipes running through the piles of sand and stone. Dolomitic and calcareous sands, however, may be injured by overheating in this manner. Furthermore, this method does not distribute the heat uniformly throughout the aggregate. Steam in radiators, or steam allowed to escape through perforated pipes placed at the bottom of the aggregate pile, is a better source of heat. Heating concrete above 150° F. should be avoided because it may produce weaker concrete.

After placement the concrete can be kept warm by covering it with a couple of feet of straw or hay, or a heavy layer of sawdust may be employed. Since these materials get mixed with the surface to some extent, their use is often objectionable.

For heating buildings in the process of construction, salamanders or box-stoves are often used. Exposed walls and floors have been heated by placing a covering of canvas or building paper a few inches from the surface of the concrete and running steam pipes between the covering and work. Special protection should be given to corners, footings, surfaces of thin members, and all parts where heat will be rapidly dissipated. The liberal use of thermometers properly placed and read frequently during the first 24 hours after pouring will provide information with regard to the need of additional heat. Minimum temperatures should not be less than 40° F. in large masses and 50° F. in smaller members. After 24 hours the heat generated by chemical activity aids in maintaining proper temperatures for continuing the process, but all work should be maintained at 40 to 50° F. for at least 72 hours after pouring. Precaution should be taken when a structure is being heated to keep the air saturated with moisture in order to prevent too rapid drying of the hardening concrete. See also papers by R. B. Young and W. Schnarr on manufacture and protection of concrete in cold weather in *Proc. Am. Conc. Inst.*, Vol. 30, pp. 279 and 292.

Tempering the mixing water with salt or calcium chloride solutions to lower the freezing point of concrete is a practice to be condemned, especially if the work is reinforced. Either of these ingredients weaken the concrete and decrease the resistance of reinforced concrete to corrosion. (See Art. 549.)

CHAPTER XIV

THE PHYSICAL PROPERTIES OF MORTAR AND CONCRETE

499. Introduction.—In this chapter we shall consider the effects of various elements and conditions which greatly influence the properties of mortar and concrete, such as strength and elastic properties, permeability to water, absorption, thermal properties, and the durability. In most cases the results given are from laboratory experiments; and it should be kept in mind that only by exercising the utmost care in selecting, proportioning and mixing materials and in the placement and curing of the concrete will it be possible to secure similar results under the conditions of practice. Also it must be recognized that many of the results represent only a limited range of variables and deductions should not be made for conditions lying without this range.

STRENGTH OF MORTARS

500. Effect of Proportion of Cement on Mortars.—The results of Feret's * tests on mortars made from fine, medium and coarse sands (Fig. 1), show, in a general way, the effect of the proportion of cement on strength. Each tension value is the average from 25 briquettes; each compression result represents five cubes 2.8 in. on a side; each transverse value was averaged from tests on 15 prisms, 0.8×0.8 in. in cross-section loaded at the center of a 3.9 in. span; and each shear test represents the average obtained from 15 halves of the transverse specimens. The latter were tested as cantilevers with the load applied close to the support. All mixes were of plastic consistency. The test-pieces were cured in water for five months before testing.

The influence of age upon the strength of water-cured mortars made from several of Wisconsin † sands and screenings is illustrated in Fig. 2. Information concerning the aggregates used in these mortars is given in Table 4, Ch. XIII.

501. Effect of Character of Fine Aggregate on Mortars.—From a large number of tests by the United States Geol. Survey (*Bulletin* No. 331), the results in Table 1 have been drawn. Mechanical analysis diagrams for several of these fine aggregates may be found in Fig. 4, Ch. XIII. These tests show in a rough way that the density and strength of mortars made of the same class of aggregates decrease as the proportion of fine grains in the aggregate increases. In strength, the mortars made of stone screenings are slightly superior to sand mortars.

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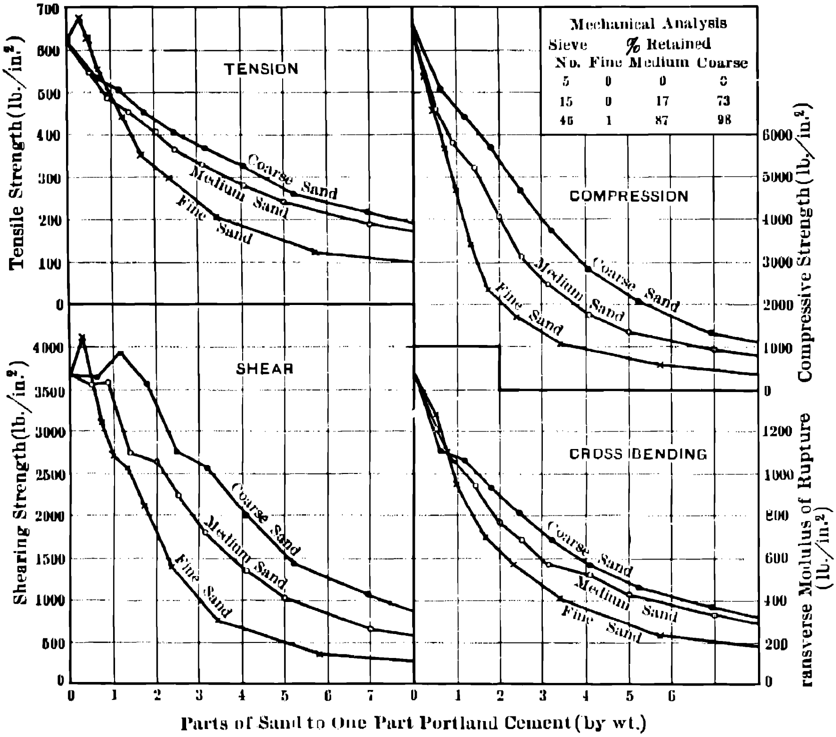
* *Bulletin de la Société d'Encouragement pour l'Industrie Nationale, 1897,* p. 1593; article by R. Feret, Chef du laboratoire des Ponts et Chaussées.

† *Proc. A. S. T. M.*, Vol. 13, p. 834.

From a series of tests on approximately 115 natural sands which were reported in *Technologic Paper* No. 58,* the relation between density (ρ) and the average compressive strength (S_c) of 2-in. cubes of 1 : 3 mortar was $S_c = 26500\,\rho - 14750$. Practically all of the strengths were within 30 per cent of the values given by this equation. In these tests a mixture of several brands of cement, a plastic consistency, hand tamping with moderate pressure, and water-storage were used. Variables in these factors as well as the character of the grains of fine aggregate will affect the constants in equations like the above.



Mechanical Analysis

Sieve No.	% Retained Fine	Medium	Coarse
5	0	0	0
15	0	17	73
46	1	87	98

FIG. 1.—Results of Strength Tests on Portland Cement Mortars of Different Proportions Made from Fine, Medium, and Coarse Sands (Feret).

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* By Wig, Williams and Gates of the U. S. Bureau of Stds.

502. Experiments on Mortars with Artificially Graded Sands.—One of the most exhaustive researches on the effects of granulometric com-

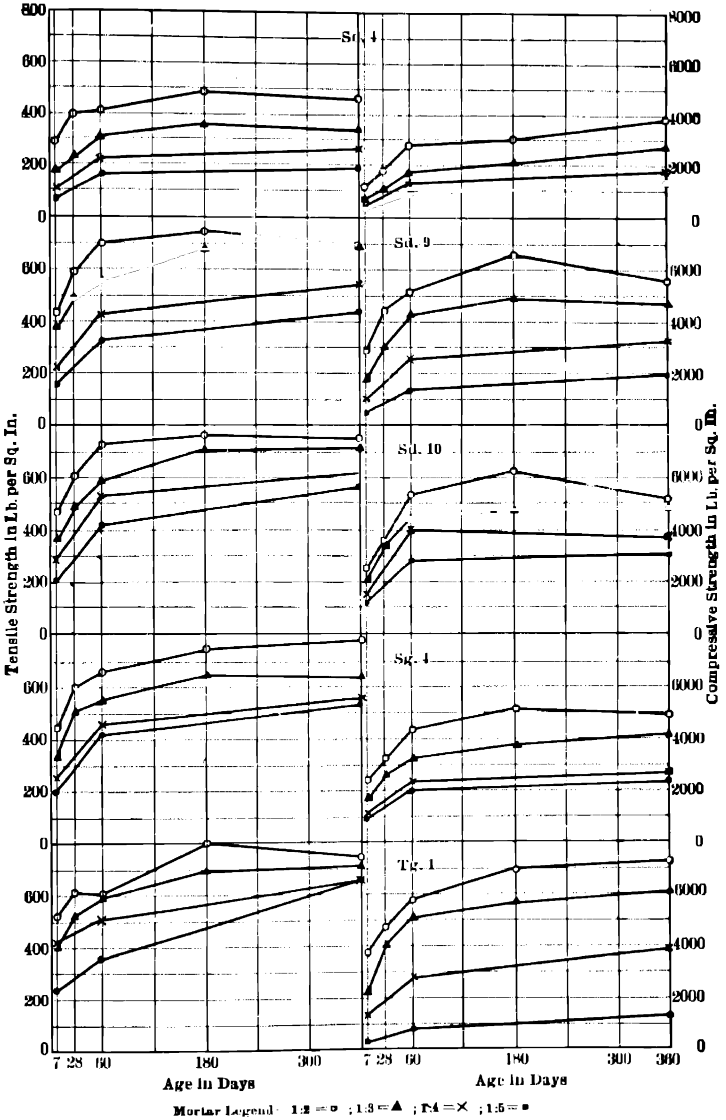

FIG. 2.—The Effect of Age on the Strengths of Water-cured Mortars Made with Portland Cement. (Each point represents three or four tests.)

position of sands has also been conducted by M. Feret. In an important series of tests he used sands graded as follows: Large grains *G* (0.2 to 0.08

TABLE 1.—EFFECT OF GRADATION OF SIZES OF PARTICLES OF AGGREGATE ON STRENGTH, DENSITY, AND YIELD OF 1 : 3 MORTARS OF PORTLAND CEMENT

(U. S. Geol. Sur., *Bull.* No. 331)

Aggregate No.	Per Cent Retained on Sieve No.				Per Cent Voids.	Yield.	Density.	Strength at 180 days in Lb. per Sq.In.		
	10	30	50	100				Tensile.	Compressive.	Transverse.
Sd. 13	31	77	93	99	28.9	1.21	.754	668	7183	1314
Sd. 16	40	79	95	99	29.7	1.20	.760	605	7108	984
Sd. 19	27	70	92	98	26.9	1.19	.789	773	6719	
Sd. 20	23	64	83	97	28.0	1.16	.794	670	6200	
Sd. 11	32	63	80	94	36.0	1.13	.730	708	5067	1272
Sd. 10	6	33	73	95	31.6	1.18	.743	488	4639	
Sd. 1	3	43	79	84	32.5	1.18	.742	415	3677	1056
Sd. 21	1	17	80	99	40.9	1.05	.700	380	2892	
Sd. 15	1	5	39	93	40.5	1.13	.676	331	2633	792
Sg. 4	74	85	90	94	36.0	1.08	.755	939	8644	1602
Sg. 6	68	82	86	88	33.1	1.11	.760	750	8048	1326
Sg. 10	50	78	88	92	31.8	1.11	.763	767	7394	1218
Sg. 3	35	57	73	85	37.0	1.09	.733	809	6500	1410
Sg. 12	31	66	79	87	35.1	1.13	.733	717	6193	1446
Sg. 7	47	82	91	94	36.1	1.07	.756	677	5279	1206
Sg. 21	6	28	47	70	41.0	1.14	.655	683	3948	
Sg. 11	10	69	54	80	42.1	1.12	.709	543	3757	918

in.), medium grains *M* (0.08 to 0.02 in.), and fine grains *F* (0.02 to 0 in.). In analyzing results he plotted points representing the proportions of the

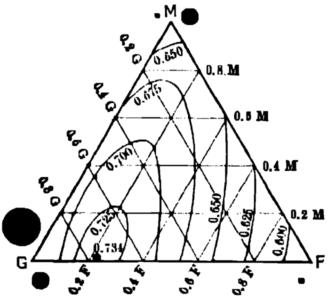

FIG. 3.—The Effect of the Gradation of the Sizes of Sand Grains on the Densities of Mortars of 1 : 3 Proportions (by weight). (The range in actual size of grain corresponding to a given letter is represented by the pair of circles at each apex in the diagram.)

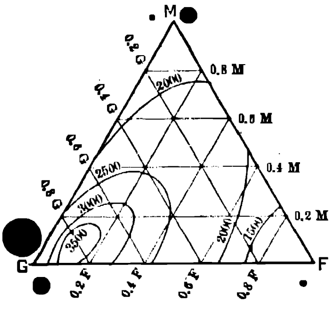

FIG. 4.—The Effect of the Gradation of the Sizes of Sand Grains on the Compressive Strength of 1 : 3 Portland Cement Mortars after Storing One Year in Fresh Water.

three sizes on equilateral triangular diagrams, the distance from any side representing the percentage of grains marked at the opposite vertex. The contour lines were then drawn through the points which corresponded to mortars of the same density, strength, etc. A comparison of Figs. 3 and 4 shows the similarity of the contours in the density and strength diagrams of 1 : 3 mortars and indicates that the maximum strength and density obtain when about five-sixths of the sand is composed of the coarse grains with fine grains constituting the principal portion of the remainder. From his experiments,* Feret drew the following conclusions:

1. With cement varying between 10 and 30 per cent of the weight of sand, the strongest mortar for any given percentage of cement was always gotten from a proportion of coarse sand equal to twice the weight of the cement plus fine sand.

2. It requires about twice as much cement mixed with a given quantity of sand to produce a mortar of given strength when fine sand is used as it does with coarse sand.

3. The weight of cement per cubic yard of mortar of a given strength is about twice as much for fine sand as for coarse sand, with the ordinary mixtures.

4. The cost per cubic yard of coarse-sand mortar of a given strength (such as is found for the ordinary ratio 1 c. : 3 s.), is only about 75 per cent of the cost of fine-sand mortar of the same strength, even when the coarse sand costs six and one-half times as much as the fine sand (coarse sand \$1.30, and the fine sand \$0.20 per cubic yard).

Feret also declared † that "for all series of plastic mortars made with the same cement and of inert sands, the resistance to compression after the same time of set under identical conditions is solely a function of the ratio $\frac{c}{e+v}$ or $\frac{c}{1-(c+s)}$, whatever may be the nature and size of the sand the proportions of the elements—sand, cement, and water—of which each is composed." In the above law e and v represent the volume of the water and air voids, respectively; the other symbols are defined in Art. 464. He derived the following relations for compressive strength:

$$S_c = j\left[\frac{c}{1-(c+s)} - 0.1\right], \text{ and } S_c = k\left(\frac{c}{1-s}\right)^2,$$

in which S_c = unit compressive strength in pounds per square inch and j and k are constants. His results indicated a value of k = 26,000 lb. per square inch. These equations with modified constants have been found to hold in other tests.*

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* *Annales des Ponts et Chaussées*, Mar., 1890, July, 1892, Aug., 1896.

† *Bull. de la Soc. d'Encouragement l'Ind. Nat.*, 1897, p. 1604.

503. Effect of Proportion of Mixing Water on Strength of Mortars.—In general, increasing the percentage of mixing water beyond that required to form a placeable mix lowers the density and strength of the mortar. The proportionate effect on strength is greatest at early ages.

In Reinke's tests† the ratios of the tensile strengths of 18 1 : 3 mortars, taking 12 per cent of water for normal consistency, to the strengths of 12 like mortars requiring 14 to 15 per cent averaged 3.9 : 1, 1.6 : 1, and 1.5 : 1 at 3, 7, and 28 days, respectively. Hence it follows that the water required for a given consistency and mix is a rough index of the strength of mortars made of clean, durable sands. The Report of the Director of Research of the Portland Cement Association shows that the strength-water-cement relation for mortars is similar to that for concretes.

504. Effect of Mica on Strength of Mortar.—Experiments by W. A. Willis ‡ on 1 : 3 mortars show that small percentages of mica decrease the tensile strength considerably. An addition of 2½ per cent of mica served to reduce the strength at seven days 11 per cent; by adding 20 per cent of mica the strength at the same age was decreased from 180 to 40 lb. per square inch. Feret also found that mica adversely effected the compressive strength. The observed effects are probably due to the weakness of the mica and to the decrease in density resulting from its presence.

505. Effect of Hydrated Lime on Strength of Mortars.—Tests by E. W. Lazell,§ Table 2, show that replacement of less than 15 per cent of the cement by hydrated lime does not decrease the tensile strength of 1 : 3 mortars. The results of E. S. Wheeler (*Report of Chief Engineer, U. S. A.*, 1896, p. 2823) are confirmatory. W. E. Emley and S. E. Young ¶ found that both tensile and compressive strengths of 1 : 3 mortars of slush consistency were adversely affected by the substitution of only 5 per cent of either high-calcium or dolomitic hydrate, if the specimens were cured in water or exposed to the weather. However, the loss in compressive strength was small for replacement of less than 25 per cent of cement by hydrate. (See also *Proc. A.S.T.M.*, Vol. 35, Pt. 2, p. 426.)

506. Adhesion of Mortars and Concretes.—Tests by E. Candlot for the French Commission show that the normal adhesion block of Art. 450 is a satisfactory specimen, but results are much affected by the character of the surface. Some results of tests on various substances by Wheeler in which 1 by 1 by ¼-in. discs were placed transversely in the minimum

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* *Proc. A.S.T.M.*, Vol. 13, p. 852.

† *Proc. A.S.T.M.*, Vol. 13, p. 797.

‡ *Eng. News*, Feb. 6, 1908.

§ *Proc. A.S.T.M.*, Vol. 8, p. 418.

¶ *Proc. A.S.T.M.*, Vol. 14, p. 339.

TABLE 2.—THE EFFECT OF THE INCLUSION OF HYDRATED LIME ON THE TENSILE STRENGTH OF 1 : 3 MORTARS OF PORTLAND CEMENT AND STANDARD SAND. (LAZELL)

Per Cent Cement Replaced by Hyd. Lime.		0	5	10	15	20	25	30	100
Method of Curing.	Age in Days.	Tensile Strengths in Lb. per Sq. In.							
In air, specimens moistened once a week	7	209	203	205	209	133	112	141	10
	28	266	258	255	245	203	170	225	44
	90	286	289	295	297	197	117	177	55
	180	382	312	304	281	229	211	219	53
	270	607	545	441	499	441	397	342	136
	360	630	456	513	642	553	444	327	168
In water after 3 days in air	7	206	157	189	239	237	173	173	
	28	278	311	364	264	268	259	268	
	90	441	389	419	372	374	314	281	
	180	358	321	341	278	260	207	253	
	270	390	301	308	279	268	250	232	
	360	426	336	311	322	299	260	231	

NOTE—Each value represents five tests.

section of a briquet are shown in Fig. 5. He found the adhesion of mortar to cut stone was not increased by roughening the surface. For sawn limestone the adhesion of neat to 1 : 2 mortars was 30 to 40 per cent of the tensile strength of the mortar. Retempering reduces adhesive strength somewhat but lessens shrinkage in setting.

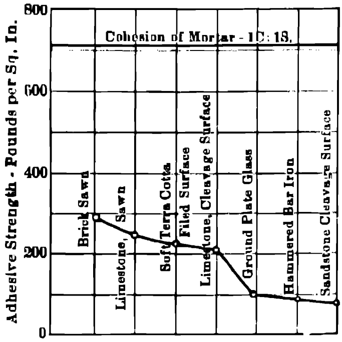

FIG. 5.—Adhesive Strength of Portland Cement Mortar, 1 C. : 1 S., Twenty-eight Days Old, to Different Substances, and the Cohesive Strength of the Mortar Itself. (Wheeler, *Rept. Chf. Engr.*, 1895, p. 3019.)

Tests on the adhesion of mortars to brick by L. A. Palmer, U. S. Bureau of Standards, *R P No. 683*, indicate that the suction rate of the surface and the strength, plasticity, and the retentivity of the mortar all vitally affect adhesion. A mortar containing 2 parts lime putty to 3 parts Portland cement to 12 parts of good mason's sand by weight, having a flow of 80 to 100 per cent (Art. 447), will usually develop at 28 days a tensile adhesion of 50 to 100 lb./in.^{2} when properly joined to brick having a suction rate between 5 and 30 g.b.m. (Art. 291).

The adhesion of concrete or mortar to plain round steel bars as rolled varies inversely with the ratio of length of bedment (l) to diameter (d). For a ratio of l/d of 25 and concrete of 3000 to 5000 lb./in.^{2} compressive strength, the average adhesion is about 500 lb./in.^{2}; for l/d of 50, the adhesion approximates 300 lb./in.^{2} For cold-rolled bars or bars with polished surfaces, the adhesion is 40 per cent less; and for square or flat bars, about 25 per cent less than for round bars with mill surface.*

STRENGTH OF CONCRETE

507. Effect of Proportion of Cement on Strength of Concrete.—With materials, consistency, and density constant, the strength of concrete increases with the proportion of cement in the mix until the strength of the cement or aggregate, whichever is the weaker, is reached. The data in Fig. 6 represent tests on moist-cured, workable concretes having the same consistency (flow of 200 and slump of 4 to 6 in.) and made from the same aggregate mixture, 38 per cent sand and 62 per cent gravel. The curves show the normal relations of strength to cement contents for these conditions. Owing to the excess of sand in the richer mixes, their densities were lower than those of the leaner mixes. This fact accounts in part for the downward droop of the upper right portions of the strength-cement-content curves. For workable mixes of drier consistencies, the corresponding curves would be higher and for those of wetter consistencies the curves would be lower. The influence of vibration in placement on the properties of concrete is well shown in Fig. 3, Art. 373, and in Art. 494.

508. The Increase in Strength of Concrete with Age.—For moist-cured concrete mixed with about 6 gal. of water per sack of cement, the Report of the Director of Research of the P. C. A. 1928 provides a large number of tests, including different aggregates from which the following percentages of 28-day strengths were developed at various ages.

Type of Test	Age at Test				
	3 Days	7 Days	28 Days	3 Months	1 Year
Compression	35	59	100	135	161
Flexure	53	71	100	126	143
Tension	46	68	100	121	150

These data show that flexural strength is gained most rapidly and the compressive strength least rapidly as age increases.

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* For further information on adhesion and bond see *Bulletin* No. 71, Engr. Expt. Sta., University of Illinois, and *Proc. Highway Res. Board*, Vol. 17, p. 150.

Studies of a large amount of test data by W. A. Slater (see *Proc. A. S. C. E.*, Jan., 1925) indicate for moist-cured concrete that the relation of the 28-day compressive strength (S_c') to the 7-day strength (S_c) is given by

$$S_c' = S_c + 30\sqrt{S_c}$$

Figure 7 contains strength-age curves for 1 : 4 mixes, by volume, made of different aggregates. The cement content was approximately constant, 6.3 sacks per cu. yd. In each mix 38 per cent of the aggregate, by weight, was Elgin sand ($m = 3.0$). The remainder was coarse aggregate of which 100 per cent passed a $1\frac{1}{2}$-in. sieve and 74 per cent passed a $\frac{3}{4}$-in. sieve. The net water-cement ratio ranged from 0.76 to 0.80, by volume, and the flow was 200. These and other data show that for ages up to a year moist-cured concrete increases in strength approximately as the logarithm of the age.

A series of experiments on the effect of age on the strength of concrete cylinders cured in three different ways was described in *Proc. Am. Conc. Inst.*, Vol. 27.

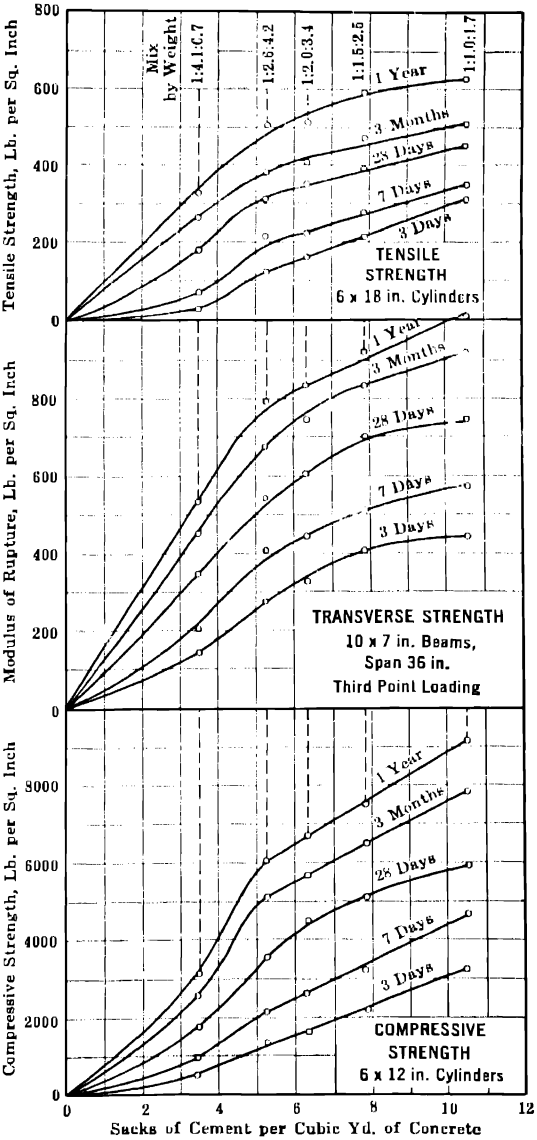

Fig. 6.—The Effect of Cement Content on the Strength of Concrete (Report of Director of Research P. C. A. 1928, Series 210). Each point represents 5 or more tests. Materials, Elgin sand and gravel graded from 0 to $1\frac{1}{2}$ in., Fineness modulus of mixed aggregate = 5.5. Flow = 200.

p. 547. The Atlas cement for these tests was mixed and stored in an air-tight tank; the proportions, amount of water, time of machine mixing and storage in molds were each made constant for the entire series of tests. Specimens from each batch of concrete were distributed throughout the various ages so that the five results gotten

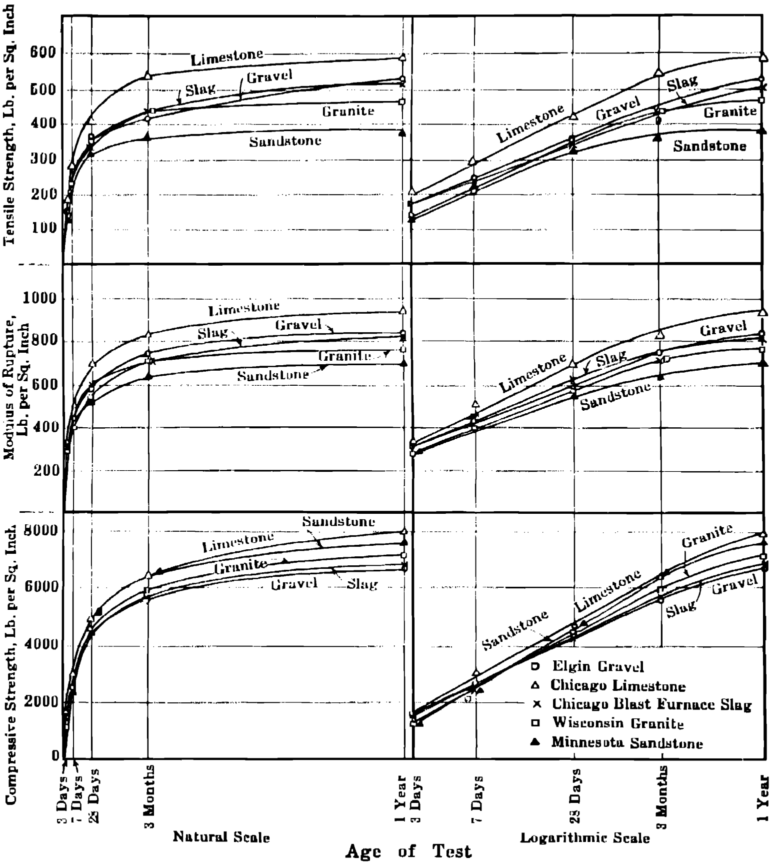

FIG. 7.—Strength-Age Relationships for Moist-Cured 1 : 4 Concrete Made of Different Coarse Aggregates (Report of Director of Research of P. C. A., 1928).

for any given test period are representative of different batches of concrete. The coarse aggregate was a limestone ranging from ¼ to 1¼ in. in size. It contained 48 per cent of voids measured loose. The sand passed a ¼-in. sieve; 38 per cent passed a No. 30 and 3 per cent passed a 100 mesh. It contained 34 per cent voids. Fig. 8 shows the strength-age relationships for these mixes over a

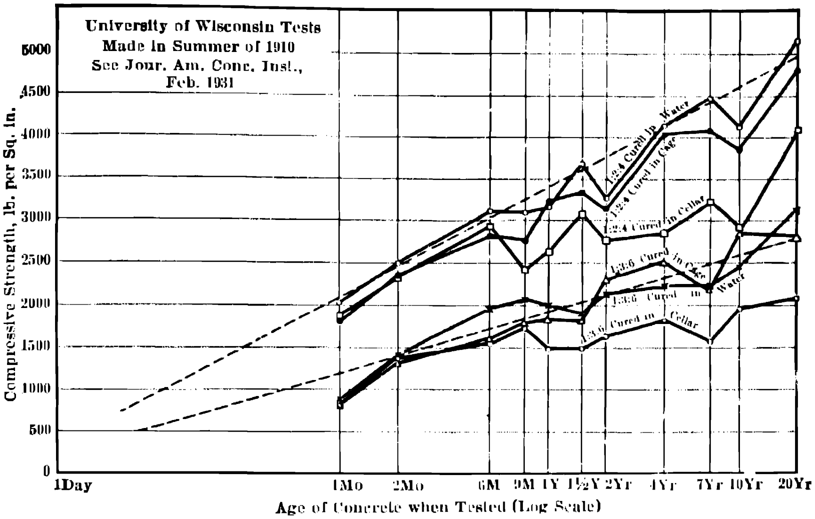

FIG. 8.—Effect of Age on the Compressive Strength of Limestone Concrete.

20-yr. period. The compressive strengths of specimens cured in water or out of doors increased approximately with the logarithm of the age, whereas those cured in the drier cellar had lower strengths. Present evidence shows that the strength-age relationships for concretes made of low-heat cements may resemble the foregoing, but those relationships for present-day normal and high-early-strength cements will exhibit maximums within a few years.

509. Effect of Density on the Compressive Strength of Concrete.—If the kind of cement and the proportion of cement per unit volume of concrete is maintained constant and if the consistency, shape of aggregate particles, age, and method of curing the concrete are the same, the strength will increase with the density. These relationships are well established in Fig. 9.

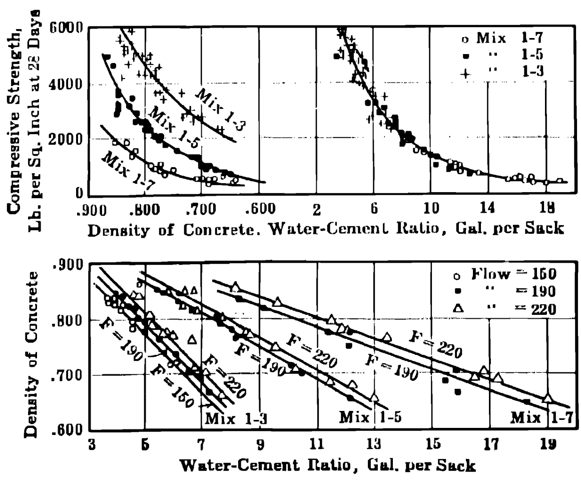

FIG. 9.—Interrelationships between Density, Strength and Water-cement Ratio for Gravel Concrete (Rep't of Director of Research of P. C. A. 1928).

Experiments have shown that the strength varies directly as the ratio $\frac{c}{1-p}$, the equation being $S_c=j\left(\frac{c}{1-p}-n\right)$. Here S_c = unit compressive strength, c = volume of cement grains in a unit volume of concrete, p = density of concrete, and j and n are constants which will vary with the factors mentioned above.* Tests at the Bureau of Standards verify this relation. The points plotted in Fig. 10 represent data from Tables 1, 23, 25 and 26, of *Technologic Paper*, No. 58, by Wig, Williams and Gates. The proportions of the concrete varied between 1 : 6 and 1 : 9 (by volume). Other conditions surrounding the making, curing and testing of the 6-in. cubes used in these tests were constant. Owing to the fact that the specific gravities of the cements used in these tests were not given, a value of 3.10

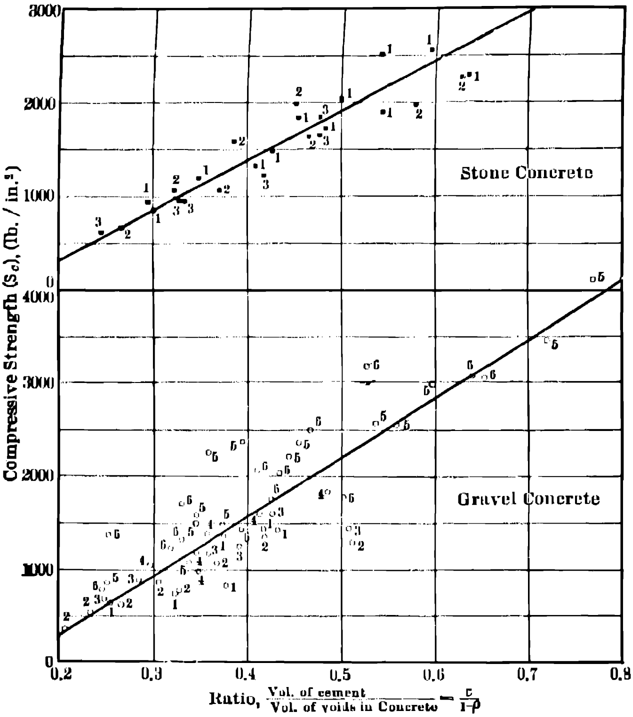

FIG. 10.—The Relation between Compressive Strength and the Ratio $\frac{c}{1-p}$

(Age of specimens 4 weeks.)

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* Further verification of this law may be found in Taylor and Thompson's *Concrete Plain and Reinforced*, 2d ed., p. 367, and in *Jour. West. Soc. Engr.*, Vol. 19. p. 837.

was assumed in making computations of c. In the figure each number represents the average result for three specimens and the like numbers indicate similar aggregates.

510. Effect of Size of Coarse Aggregate on Compressive Strength.—With the largest particles not over 6 in. in diameter, it may be stated that the larger the maximum size of the aggregate the denser and stronger will be the concrete, provided other influencing factors are eliminated. The change in strength with the increase in maximum size of aggregate is most marked for diameters under 1 in. The tests of Fuller and Thompson * on 1 : 9 concrete, which illustrate the latter statement, are shown in Table 3. The beams used in these tests were 6×6×72 in. and the spans were 60 and 30 in. The compression tests were made on prisms from the beams, approximately 6×6×19 in., which were capped on each end with neat cement.

TABLE 3.—EFFECT OF VARIATION IN THE MAXIMUM SIZE OF COARSE AGGREGATE ON THE STRENGTH AND DENSITY OF PORTLAND CEMENT CONCRETE. (FULLER and THOMPSON)

Proportion, by weight.	Material.*		Character of Mixture.	Average Density.			Average Modulus of Rupture at 90 Days, in Lb. per Sq.In.			Average Compressive Strength at 140 Days, in Lb. per Sq.In.		
	Stone.	Sand.		2¼-in. Stone.	1-in. Stone.	¼-in. Stone.	2¼-in. Stone.	1-in. Stone.	¼-in. Stone.	2¼-in. Stone.	1-in. Stone.	¼-in. Stone.
1 : 9	J. Park	J. Park	Ideal	0.851	0.810	0.767	257	226	208	1342	950	915
1 : 9	"	"	Natural	0.821	0.798	0.768	211	171	162	980	870	821
1 : 9	"	"	Uniform Aggregate	0.832	0.797	0.769	257	229	180	1350	950	890
1 : 9	Cowe* Bay	Cowe Bay	Various	0.859	0.847	0.853	243	246	189	1486	1402	1231
1 : 9	J. Park	Cowe Bay	"	0.872	0.818	0.784	291	273	207	1798	1585	1185
			Averages	0.847	0.814	0.788	252	229	189	1391	1153	1008
			Ratios	1.00	0.96	0.93	1.00	0.91	0.75	1.00	0.83	0.72

* Jerome Park stone was a crushed mica schist, the sand was screened from the crusher-run material. Cowe Bay material consisted of gravel and sand.

NOTE.—A soft mushy consistency was used in all tests. Aggregates were well graded.

The ideal mixture was graded in accordance with a fixed sieve analysis curve.

Tests by Abrams, Fig. 11, show that the strength of concrete of a given consistency increases with the fineness modulus (Art. 470) of the mixed aggregate, provided the limits of workability are not exceeded. The peaks of the curves in Fig. 11 indicate that coarser gradings, as evidenced by higher fineness moduli, may be permitted in rich mixes like 1 : 4 than in lean mixes like 1 : 9. Fig. 12 shows relation of compressive strength to fineness modulus when the maximum size of aggregate ranges up to 2 in.

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* *Trans. A. S. C. E.*, Vol. 59, p. 115.

If there are no large gaps in the grading of the aggregate particles, the fineness modulus of the mixed aggregate is of assistance in estimating the workability of mix. Experience has shown that it is not practicable to increase the fineness modulus beyond certain limits shown in Table 4. These limits are dependent upon the character and maximum size of aggregate, the richness of the mix, and the use for the concrete.

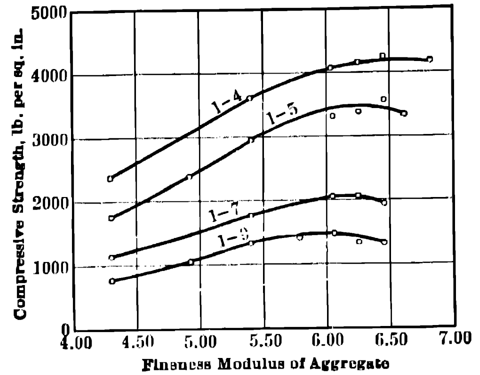

FIG. 11.—Effect of Fineness Modulus of Aggregate on Strength of Concrete. (Abrams).

Each point represents 5 tests of 6 × 12-in. cylinders; slump = ½ in.; age = 28 days; aggregate was sand and pebbles graded up to 1½ in. in diameter.

In the construction of large dams by the Bureau of Reclamation many tests were made on concrete containing aggregate up to 9 in. in diameter (see paper by R. F. Blanks and C. C. McNamara, *Proc. Am. Conc. Inst.*, Vol. 31, p. 280, 1935; Vol. 32, p. 234). The results showed an increase of 16 per cent in the strength of concrete per barrel of cement used due to a change in maximum size of gravel from 1 to 3 in. and an increase of 29 per cent due to a change from 1 to 6 in. The fineness moduli of the aggregates passing the 3-in. and 6-in. openings were 7.83 and 8.25, respectively, and their dry-rodded void contents 31.8 and 29.1 per cent.

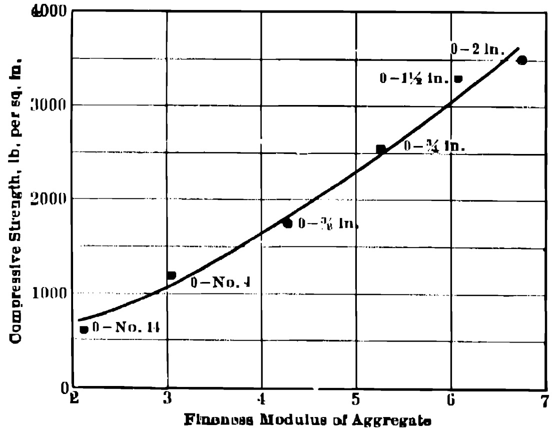

FIG. 12.—Effect of Gradation of Aggregate on Strength of Concrete. (Abrams.)

Each point represents 5 tests on 6 × 12-in. cylinders of 1 : 5 proportions at 28 days. Aggregate was sand and pebbles. Slump = ½ in.

TABLE 4.—MAXIMUM PERMISSIBLE VALUES OF FINENESS MODULUS OF AGGREGATES. (ABRAMS)

For *mixes* other than those given in the table, use the values for the next leaner mix.

For *maximum sizes* of aggregate other than those given in the table, use the values for the next smaller size.

This table is based on the requirements for *sand-and-pebble or gravel* aggregate composed of approximately spherical particles, in ordinary uses of concrete in reinforced concrete structures. For other materials and in other classes of work the maximum permissible values of fineness modulus for an aggregate of a given size is subject to the following corrections:

(1) If *crushed stone* or *slag* is used as coarse aggregate, *reduce* values in table by 0.25. For crushed material consisting of unusually flat or elongated particles, *reduce* values by 0.40.

(2) For *pebbles* consisting of *flat particles, reduce* values by 0.25.

(3) If *stone screenings* are used as fine aggregate, *reduce* values by 0.25.

(4) For the top course in *concrete roads*, or other work requiring a smooth finish, *reduce* the values by 0.25. If finishing is done by *mechanical means*, this reduction need not be made.

(5) In work of *massive proportions*, such that the smallest dimension is larger than 10 times the maximum size of the coarse aggregate, *additions may be made* to the values in the table as follows: for ¾-in. aggregate, 0.10; for 1½-in., 0.20; for 3-in., 0.30; for 6-in., 0.40.

Sands with fineness modulus lower than 1.50 are undesirable as fine aggregate in ordinary concrete mixes. Natural sands of such fineness are seldom found.

Sand or screenings used for fine aggregate in concrete must not have a higher fineness modulus than that permitted for mortars of the same mix. Mortar mixes are covered by the table and by (3) above.

Crushed stone mixed with both finer sand and coarser pebbles requires no reduction in fineness modulus provided the quantity of crushed stone is less than 30 per cent of the total volume of the aggregate.

	Size of Aggregate.	Proportions (by Volume). Aggregate: Cement.								
		1	2	3	4	5	6	7	9	12
	Sieve No.									
Mortars	0–28	2.25	2.00	1.85	1.70	1.60	1.50	1.40	1.30	1.20
	0–14	3.00	2.70	2.50	2.30	2.15	2.05	1.95	1.85	1.80
	0– 8	3.80	3.40	3.10	2.90	2.75	2.65	2.55	2.45	2.40
	0– 4	4.75	4.20	3.90	3.60	3.45	3.30	3.20	3.05	2.95
	0– 3*	5.25	4.60	4.30	4.00	3.80	3.65	3.55	3.45	3.35
	In.									
Concretes	0–⅜	5.60	5.05	4.70	4.40	4.20	4.05	3.95	3.85	3.80
	0–½*	6.05	5.45	5.10	4.80	4.60	4.45	4.35	4.25	4.20
	0–¾	6.50	5.90	5.50	5.20	5.00	4.85	4.75	4.65	4.60
	0–1*	6.90	6.30	5.90	5.60	5.40	5.25	5.15	5.00	5.00
	0–1½	7.35	6.70	6.30	6.00	5.80	5.65	5.55	5.40	5.35
	0–2.1*	7.75	7.10	6.70	6.40	6.20	6.05	5.95	5.80	5.75
	0–3	8.20	7.55	7.15	6.85	6.60	6.50	6.40	6.25	6.20
	0–4½*	8.65	7.95	7.55	7.25	7.00	6.90	6.80	6.65	6.60
	0–6	9.10	8.40	8.00	7.65	7.45	7.30	7.20	7.05	7.00

* Half sieves; not used in computing fineness modulus.

511. Effect of Proportion of Water on Strength of Concrete.—For a given cement content, the greatest strength at an early age can be secured from a concrete of dry consistency in which there is only sufficient water for perfect hydration of the cement. Such concrete requires heavy ramming or vibration to make it homogeneous and dense. A somewhat wetter consistency, slump 1 to 2 in., is much more workable and furnishes approximately as high strength. If the cement content is maintained constant and the proportion of mixing water is increased the strength decreases.

As previously mentioned (Art. 482), Abrams demonstrated that for workable mixes the strength of concrete is an inverse function of the water-cement ratio, regardless of the cement content. Fig. 13, from the Report of the Research Director of the P.C.A. 1928, shows the relationships between the water-cement ratio and the compressive strength, tensile strength, and modulus of rupture for concrete made of sand and gravel and tested at the ages indicated. Each point represents 5 tests. It will be observed from Fig. 13 that the relationship is independent of cement content, consistency, and size and grading of aggregate. Abrams' original diagram, *Bulletin No.* 1, Structural Materials Research Laboratory, Lewis Institute, covered a somewhat wider range in water-ratio and mix proportions for 28-day compressive strengths, but lacked in other respects the scope of Fig. 13.

Evidence that for workable mixes the water-ratio relationship covers the effects of variables in density, cement content, and consistency is well shown in Fig. 9 by the plotting of the data of the various relationships into the single water-ratio curve.

Variations in quality of cement, in the structural characteristics of the aggregate and in curing conditions affect the water-ratio strength relationship. Hence it is desirable in important work to secure this relationship for the materials and conditions on the work. The data in Table 5, taken from the curves of Fig. 13, are representative of the effect of the water-ratio on the early strength of concrete.

TABLE 5.—REPRESENTATIVE STRENGTHS FOR DIFFERENT WATER-CEMENT RATIOS *

Water-Cement Ratio			Compressive Strength, Pounds per Square Inch		Modulus of Rupture, Pounds per Square Inch		Tensile Strength, Pounds per Square Inch	
By Volume	By Weight	Gallons per Sack	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
0.60	0.40	4.5	4000	5700	550	725	330	440
0.80	0.53	6.0	2300	4000	410	580	230	340
1.00	0.66	7.5	1300	2600	280	430	140	240
1.20	0.80	9.0	800	1600	180	325	80	170

* From Report of the Director of Research of the P. C. A., 1928.

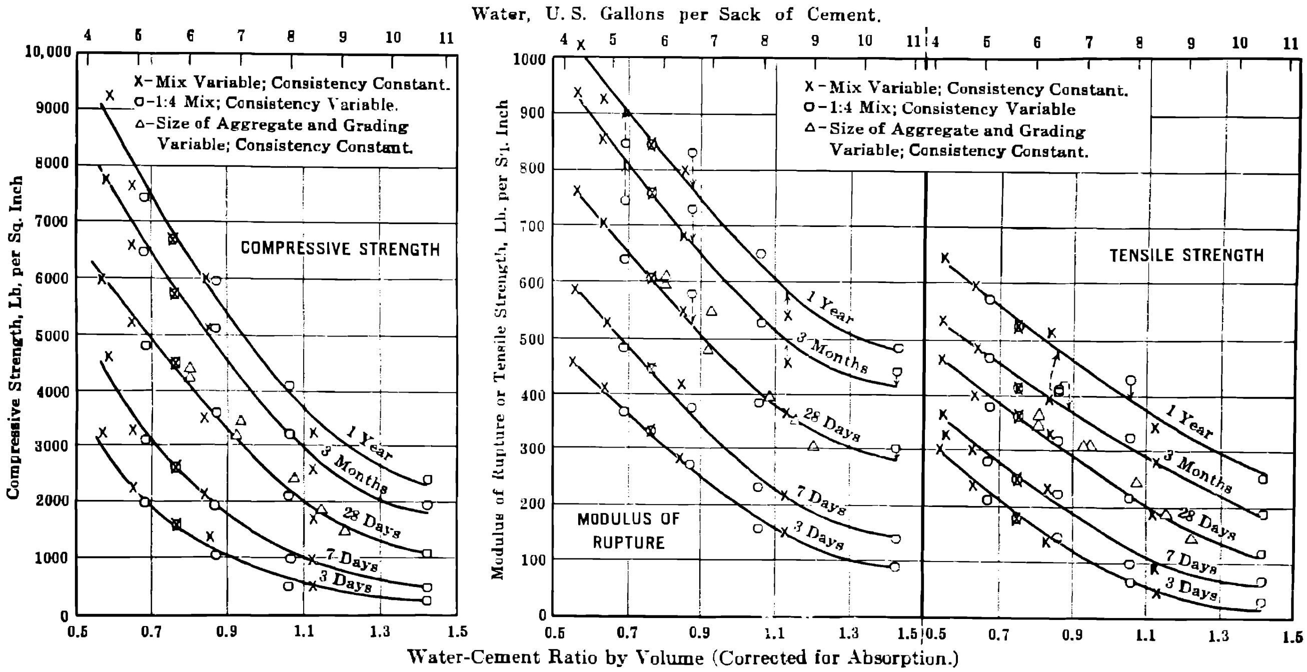

FIG. 13.—Relationships between Compressive, Flexural, and Tensile Strengths of Moist Cured Concrete and the Water-cement Ratio (Rep't of Director of Research of P. C. A. 1928). Compression and tension tests on 6×12-in. cylinders; flexure tests on 10×7×38-in beams. Aggregate, Elgin sand and gravel.

512. Tensile Strength of Concrete.—In general, the tensile strength of concrete varies between one-eighth and one-twelfth of its compressive strength. Besides the affecting conditions discussed under compressive strength tests, imperfections in the fabrication of specimens, the tensile strength and surface characteristics of the aggregate and the method of gripping and loading greatly affect the tensile strength of concrete. Owing to the influence of these factors the results of tension tests are generally less uniform than those gotten in compression.

The effects of cement content, age, and water-ratio on the tensile strength of moist-cured gravel concrete are well illustrated in Figs. 6 and 13. Fig. 14 from the Report of the Research Director of the P.C.A., illustrates the effect of grading on the tensile strength of concrete. In a general way the tensile strength increases as the fineness modulus is increased, or the grading is made coarser, until the coarseness causes the mix to become harsh in working. The maximum permissible degree of coarseness is dependent upon the same factors that govern the compressive strength, see Table 4.

The tensile strength is also affected by the character of the surface of the aggregate and its tensile strength. Fig. 7 shows that the tensile strength of the concrete made of Chicago Limestone was approximately 20 per cent greater than that made of Elgin gravel or slag, 25 per cent stronger than that of Wisconsin granite, and 40 per cent stronger than the concrete of Minnesota sandstone.

A convenient form of specimen for use in tension tests on concrete * is a 6 by 18-in. cylinder. In the tests at the Portland Cement Association Laboratory, each end of such cylinder was gripped in a section of steel tubing which had been slit into quadrants and attached to heavy end plates. To each quadrant was riveted a piece of channel with flanges extending radially outward. The tubing was lined with leather $\frac{1}{8}$-in. thick to provide a uniform friction grip on the test pieces. Each grip was squeezed against a specimen over a 5-in. length by tightening bolts inserted in the outstanding flanges of the channels. The load was applied to the grips by two heavy bolts, one for each grip, which passed through the heavy end plates. Each bolt was provided with a spherical seated nut at each end.

513. The Transverse Strength of Concrete.—The effects of cement content, age, water-ratio, and kind of coarse aggregate on the modulus of rupture of concrete are well shown in Figs. 6, 7 and 13. Fig. 14 shows the effect of changing the grading of the aggregate on the modulus of rupture. It will be noted that somewhat coarser gradings can be more effectively used in the production of high flexural strength than in securing maximum compressive or tensile strength.

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* For descriptions of other types of test pieces see Mills, *Cornell Civil Engr.*, Vol. 19, p. 106; Talbot in *Bull.* No. 1, Univ. of Ill., Expt. Sta.; Withey in *Bull.* No. 197, Univ. of Wis.

Like the tensile strength, the modulus of rupture appears to be affected by the shape, character of the surface of the aggregate and its tensile strength, as shown in Fig. 7.

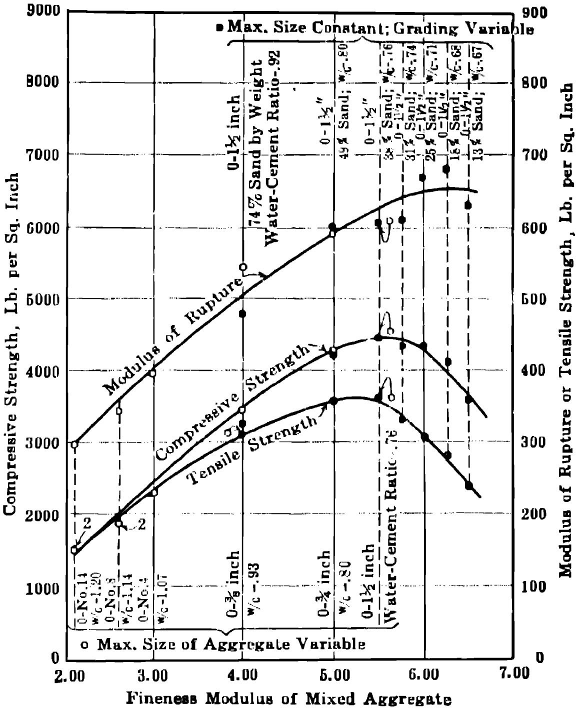

FIG. 14.—Effect of Size and Grading of Aggregate on the Strength of Moist-cured 1 : 4 Concrete (Rep't of Director of Research of P. C. A. 1928). Aggregate, Elgin sand and gravel; flow, 200 per cent; age 28 days.

For moist-cured concrete of well-graded limestone or gravel having a water-ratio of 0.80, by volume, or 6 gallons per sack of cement, the ratio of the modulus of rupture to the compressive strength approximates the following values: at 7 days $\frac{1}{5}$, at 28 days $\frac{1}{7}$, and at one year $\frac{1}{8}$. A large amount of data in the Report of the Research Director of the P. C. A. indicates that for moist-cured concrete of Elgin gravel —mix, age, grading and consistency being included variables,—the modulus of rupture, $S_m=200+0.09S_c$, when S_c, the compressive strength, is between 1500 and 9000 lb./in^2.

The continued growth in strength of concrete over a one-year period is, to a large extent, dependent upon the amount of moisture given the specimens during curing. The adverse effect on strength of a dry curing condition is more pronounced as the age of the specimen increases. The flexural strength does not appear to be affected as seriously by dry curing as the compressive strength. Relative strengths based on damp curing are given in Table 6.*

514. The Shearing Strength of Concrete.—Failure of concrete in pure shear is a rare occurrence. When this term " shear failure " is

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* From Series 171, Report of Director of Research of P. C. A.

TABLE 6.—THE EFFECT OF CURING CONDITIONS ON STRENGTH OF 1 : 4 CONCRETE

Curing	Coarse Aggregate	Relative Strengths of Concrete in Per Cent							
		Compressive Strength				Modulus of Rupture			
		7 Days	28 Days	3 Months	1 Year	7 Days	28 Days	3 Months	1 Year
Under wet burlap; tested damp	. . . .	100	100	100	100	100	100	100	100
Air of laboratory; tested dry.	Gravel	90	84	75	65	84	77	78	75
	Limestone	101	85	80	62	95	86	90	87
Air of laboratory; tested wet.	Gravel	91	65	54	49	101	110	96	81
	Limestone	102	62	61	53	110	110	107	98
Air of laboratory; sodium silicate coated, tested as cured.	Gravel	98	89	76	65	101	90	87	76
	Limestone	104	75	72	61	91	85	84	87

applied to the diagonal failure in the web of a concrete beam it is misleading, for the cause of such failure is a tensile stress resulting from the combining of tensile and shearing stresses. On account of the difficulty of producing a pure shear stress but few tests have been made. The usual method of making such tests is to support the specimen as a cantilever or fixed beam and apply the load as closely as possible to the supports. Frequently encircling envelopes are placed at each support and around the span portion to prevent bending of the test-piece.

In E. Mörsch's *Eisenbetonbau* (translation by E. P. Goodrich), Ch. III, the theory is advanced that the shearing strength of concrete (S_s) is the geometric mean of its tensile (S_t) and compressive strength (S_c), $S_s = \sqrt{S_t \times S_c}$. Mörsch's results obtained from tests on 7×7×16-in. prisms loaded as indicated in Fig. 15 are in accordance with this theory. However, since in these tests the concrete cracked in tension before the full shearing strength was developed, one is led to believe that the computed values of shear are much too low. Mörsch also tested the torsional strength of solid concrete cylinders 10.24 in. in diameter by 13.38 in. long and hollow cylinders of the same outside measurements with an internal diameter of 5.9 in. The proportions were 1 : 4 gravel concrete and the ages of the solid and hollow specimens three months and two months, respectively. The modulus of rupture in torsion (see formula 17 in Art. 23) for four solid cylinders averaged 243 lb. per square inch, for three hollow cylinders 126 lb. per square inch. All specimens fractured on helicoidal surfaces. Tensile tests on like hollow sections gave a strength of 133.8 lb. per square inch. Apparently the torsional strength is equal to the tensile strength if the specimen is dimensioned so that the intensity of the shearing stress is approximately the same over the entire cross-section. Mörsch also reports results of tests on slotted beams

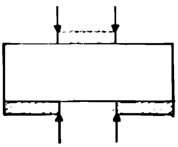
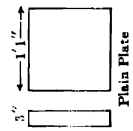
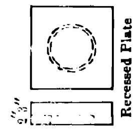
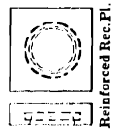


FIG. 15. — Morsch's Shear Specimen.

reinforced in the tension fibers so that failure in horizontal shear along a small portion of the neutral plane was produced. Here again it seems certain that diagonal tension must have largely influenced the results.

TABLE 7.—SUMMARY OF RESULTS OF SHEAR TESTS ON BROKEN STONE CONCRETE MADE AT UNIVERSITY OF ILLINOIS AND MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Mix by Vol.	Stored in.	No. Tests.	Strength in Lb. per Sq. In in		Ratio Shear* / Compr.	Form of Specimen.
			Shear.	Compression.*		
		University of Illinois Tests. Age 2 Months.				
1 : 3 : 6	Air	9	679	1230	0.55	
1 : 3 : 6	Water	7	729	1230	0.59	
1 : 3 : 6	Damp Sand	4	905	2428	0.37	
1 : 2 : 4	"	5	1193	3210	0.37	
1 : 3 : 6	Air	17	796	1230	0.65	
1 : 3 : 6	Water	5	879	1230	0.71	
1 : 3 : 6	Damp Sand	4	1141	2428	0.47	
1 : 2 : 4	"	5	1257	3210	0.39	
1 : 3 : 6	Air	4	1051	1230	0.86	
1 : 3 : 6	Damp Sand	4	1821	2428	0.75	
1 : 2 : 4	"	5	2145	3210	0.67	
1 : 3 : 6	Damp Sand	4	1313	2428	0.54	4×4×12 in. beams restrained at ends
1 : 2 : 4	"	6	1418	3210	0.44	
		Tests at Mass. Inst. of Tech. Age 1 Month.				
1 : 2 : 4	Air	......	1310	2070	0.63	5×15 in. cylinders restrained at ends and loaded over span $5\frac{7}{16}$ in. long by a half cylinder bearing.
1 : 2 : 4	Water	......	1650	2620	0.63	
1 : 3 : 5	Air	......	1240	1310	0.94	
1 : 3 : 5	Water	......	1120	1360	0.82	
1 : 3 : 6	Air	......	1180	950	1.25	
1 : 3 : 6	Water	......	1120	1270	0.88	

* Illinois specimens were 6-in. cubes; M.I.T. specimens were 5×18-in. cylinders.

NOTE.—In Illinois tests limestone passed 1-in. mesh. Trap rock passing 1¼ in. ring was used at M. I. T.

The results of shearing tests on 5-in. cylinders of concrete made at the Mass. Inst. of Technology under the direction of C. M. Spofford* are digested in Table 7. In these tests the end and center portions of the cylinders were tightly clamped so that bending action was made small. The results indicated such an abnormally high ratio of shearing to compressive strength that one is led to believe frictional resistance must have been induced at the planes of fracture. Specimens cured in water for one month appear to be slightly stronger in shear than those cured in air.

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* See Reid's *Concrete and Reinforced Concrete Construction*, p. 198.

A very comprehensive series of tests by Talbot * included punching tests on plane plates, on recessed plates, and on plates reinforced and recessed as shown in Table 7. The punch used was a cylinder $5\frac{7}{8}$ in. in diameter which acted through the specimens against a die 6 in. in diameter. Talbot reported that the reinforced recessed plates were the most satisfactory of the types of specimen used in the punching tests. He also used short beam test-pieces restrained at the end in a device like the Johnson shear tool (Art. 56) and applied the load across the span uniformly but without restraining the center portion of the beam.

The existing data indicate that the shearing strength of concrete lies between 40 and 60 per cent of the compressive strength.

515. The Effect of Fatigue on Concrete.—The resistance of plain concrete to fatigue deserves consideration in many structures but particularly in pavements. Tests of concrete six months, or more, in age under loads rapidly repeated for 5,000,000 cycles indicate that the endurance limit (Art. 824) of air-dry concrete in compression or in bending is approximately 50 to 55 per cent of the corresponding strength under loading progressively applied to failure. Tests of mortars saturated with water indicate that the endurance limit is only about 40 per cent of the strength of air-dry mortar under progressive loading. Hatt † states that beams reinforced with small percentages of steel mesh show an increase of about 13 per cent in strength and 7 per cent in extension as compared to similar plain beams when subjected to repeated loadings.†

516. Resistance of Concrete to Wear.—In *Bulletin* 10, Structural Materials Research Laboratory, Abrams gives results of wear tests on about 10,000 8 by 8 by 5-in. concrete blocks. These blocks were tested in groups of 10 in a Talbot-Jones rattler. In testing, the blocks were wedged securely to form the lining to the rattler drum and were subjected to the abrasion and impact of a 200-lb. charge of cast-iron balls while the machine ran one hour at 30 r.p.m. Wear was measured by loss in weight, but expressed as depth lost in inches.

Abrams found that the quality of the concrete was the most important factor which affected the resistance to wear. He found that the wear (W) decreased with the compressive strength of the concrete (S_c) and could be expressed by the relationship $S_c = \frac{A}{W^n}$, in which A and n are constants depending on quality of concrete and method of test. For one series of

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* *Bulletin* No. 8, University of Illinois.

† For further data see *Bulletin* No. 34, Eng. Expt. Sta. Purdue University; also *The Fatigue of Metals* by Kommers and Moore.

TABLE 8.—THE COMPRESSIVE STRENGTH AND SPECIFIC WEIGHT OF CINDER CONCRETE

No. Spec.	Mix by Vol.	Consistency	Age in Months.	Compressive Strength, Lb. per Sq. In.	Specific Weight, Lb. per Cu. Ft.	Type of Specimen.	How Cured.	Authority.
3	1 : 1 : 3	Dry	1	1466	112.1	12-in cubes	Air	*Tests of Metals.* 1908
3	1 : 1 : 3	Dry	3	2001	110.4			
3	1 : 2 : 3	Dry	1	1098	115.2			
3	1 : 2 : 3	Dry	3	1634	112.8			
3	1 : 2 : 4	Dry	1	904	111.2			
3	1 : 2 : 4	Dry	3	1325	107.9			
3	1 : 2 : 5	Dry	1	769	108.8			
3	1 : 2 : 5	Dry	3	1084	105.3			
3	1 : 2 : 6	Dry	1	529	107.6			
3	1 : 2 : 6	Dry	3	788	103.5			
3	1 : 2 : 5	Wet	1	1081		8×16-in. cyl.	Moist air	U.S. Geol. Sur. *Bull.* No. 344.
3	1 : 2 : 5	Medium	1	1201				
3	1 : 2 : 5	Damp	1	1118				
3	1 : 2 : 5	Wet	3	1764	116.5			
3	1 : 2 : 5	Medium	3	1819	115.6			
3	1 : 2 : 5	Damp	3	1726	112.5			
3	1 : 2 : 5	Wet	6	2021	113.9			
3	1 : 2 : 5	Medium	6	2203	114.3			
3	1 : 2 : 5	Damp	6	1945	113.7			
10	1 : 2 : 5	Consistency not stated. Concrete taken from 4 buildings in N. Y. City.	1	407	107	8×16-in. cyl.	Air	Strehan and Perrine in *Engr. News* Vol. 70 p. 722
10	1 : 2 : 5		2	701				
10	1 : 2 : 5		6	933				
10	1 : 2 : 5		1	818	107			
10	1 : 2 : 5		2	1254				
10	1 : 2 : 5		6	1744				
10	1 : 2 : 5		1	980	109			
10	1 : 2 : 5		2	1035				
10	1 : 2 : 5		6	1478				
10	1 : 1 : 5*		1	507	100			
10	1 : 1 : 5		2	662				
10	1 : 1 : 5		6	754				

* Hand-mixed, the other batches of this group were machine-mixed.

300 tests he reports $A = 2230$ and $n = 1.07$. For concrete of the type used in road construction, his tests show that the resistance to wear increases directly with the compressive strength. From his tests Abrams concluded that the quality of the aggregate did not have as potent an effect on the amount of wear as the water-cement ratio or proportion of cement.

The experience of one of the authors in conducting several hundreds of similar wear tests on slabs 8 by 20 by 4½-in. in a modified brick rattler has demonstrated that with a properly proportioned mix of well-graded materials, the uniformity of wear and the amount of wear are both considerably affected by the quality of the aggregate. A concrete of tough angular crushed dolomite will in most cases wear less and more evenly than a like concrete made of pebble aggregate. The two main reasons for this difference are the greater uniformity of the crushed stone in strength and toughness and the better bond which it affords the mortar.

517. The Strength of Light Weight Concrete.—On account of its fireproofing properties and its light weight, cinder concrete is considerably used for floor construction and for a fireproofing shell around beams and columns. The strength of cinder concrete is decidedly variable and is greatly influenced by the strength, granulometric composition, and absorptive properties of the cinders. Table 8 shows the results of tests made by various experimenters. The results of the tests by the U. S. G. S. show that consistency has but little effect on the compressive or transverse strength of cinder concrete. From the latter tests on 6-in. cubes and 8×11-in. beams on a 12-ft. span, the ratio of the compressive strength to the transverse modulus of rupture averages 9.8 : 1 for concrete six months old. It will be noted that this ratio is considerably larger than the corresponding value for gravel or broken stone concrete.

For purposes of construction similar to those mentioned in discussing cinder concrete, slag concrete is sometimes used. The results given in Tables 9 and 10 are taken from *Furnace Slags*, issued by the Carnegie Steel Co., Pittsburgh. Each compressive strength result is the average of three tests on 12×16-in. cylinders. All specimens were made of standard Portland cement. They were daily sprinkled with water for twenty-seven days after making. The results show that the slag sand No. 2 made by running the molten slag into a water vat is slightly superior to slag sand No. 1 which was run through a spray as it fell into the water vat. The crushed bank slags, No. 1 and No. 2, produced a stronger concrete than the machine slag which was disintegrated by sprinkling with water after it had partially cooled.*

Haydite, an aggregate made by crushing a bloated burnt clay, also makes a strong and fire-resistant concrete. During the War, this material

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* For additional tests on slag concrete, see Fig. 8; Symposium No. 18 of the National Slag Association; and *Engr. News*, Vol. 72, p. 103 and Vol. 75, p. 276.

TABLE 9.—THE COMPRESSIVE STRENGTHS OF SLAG CONCRETES OF 1 : 3 : 6 : PROPORTIONS BY VOLUME

Sand.	River	No. 1 Slag	No. 2 Slag	River	No. 1 Slag	No. 1 Slag	River	No. 1 Slag	No. 2 Slag
Coarse Aggregate	No. 1 Bank Slag	No. 1 Bank Slag	No. 1 Bank Slag	Machine Slag	Machine Slag	Machine Slag	No. 2 Bank Slag	No. 2 Bank Slag	No. 2 Bank Slag
Age	Compressive Strength in Lb. per Sq.In.								
28 da.	1033	863	963	670	561	708	1028	697	837
90 da.	1377	1100	1228	928	826	994	1307	1040	1076
6 mo.	1478	1222	1363	854	983	1057	1440	981	1225
1 yr.	1722	1131	1309	902	1038	1052	1328	666	1232
2 yr.	1778	959	1367	1200	836	960	1888	1030	1348
Wt. in lb./ft.^{3}	138	121	131	129	120	122	137	129	128

TABLE 10.—PROPERTIES OF AGGREGATES IN SLAG CONCRETES

Element.	Chemical Analyses.					Mechanical Analyses.			
	Per Cent of Element in					Mesh.	Per Cent Passing.		
	River Sand.	Slag Sand No. 1	Slag Sand No. 2	Bank Slag.	Machine Slag.		River Sand.	Slag Sand No. 1.	Slag Sand No. 2.
SiO_2	79.28	30.31	32.24	37.26	31.28	10	87.5	75.0	75.4
Al_2O_3	8.23	20.72	16.32	16.62	17.40	20	74.6	36.3	34.4
CaO	5.60	44.67	46.51	39.26	46.20	30	50.0	15.6	16.0
MgO	0.92	1.48	1.45	3.06	1.43	40	28.1	9.8	11.3
Fe_2O_3	0.59	1.43	1.91	2.50	1.52	50	17.2	7.8	10.2
SO_3	5.38	1.39	1.57	1.30	1.56	80	1.6	4.3	5.5
						100	0.8	3.1	3.5

Other Properties.

	River Sand.	Slag Sand No. 1	Slag Sand No. 2	Bank Slag.		Machine Slag.
Size				No. 1 ½"–1"	No. 2 1"–2½"	1"–2"
Wt. in lb./ft.^{3}	106	55	49	67	72	96

was used to make concrete ships. Crushed to pass a $\frac{3}{16}$-in. screen, the fine aggregate weighed about 70 lb. per cu. ft. and the coarse aggregate which passed a $\frac{5}{8}$-in. screen and was retained on a $\frac{3}{16}$-in. screen weighed 45 lb. per cu ft. Mixed in 1 : $\frac{2}{3}$: 1$\frac{1}{3}$ proportions by volume with about 22 per cent of water, by weight of dry materials, this concrete had a slump of 8 to 10 in. and weighed when green 114 lb. per cu. ft. At 28 days numerous tests showed that the compressive strength averaged above 4000 lb. per sq. in. (*Engr. News-Record,* Vol. 82, p. 802). Other tests on cylinders of 1 : 6 Haydite concrete which had been subjected to temperatures between 1500 and 1800° F. for 5 hr. showed that the compressive strength, 2835 lb. per sq. in., was reduced about 55 per cent by exposure to these high temperatures (see *Engr. News-Record,* Vol. 87, p. 765; see also paper by Richart and Jensen, *Proc. A.S.T.M.*, 1930).

THE ELASTIC PROPERTIES OF MORTARS AND CONCRETES

518. General Characteristics of the Elastic Curves.—As Fig. 16 shows, the stress-deformation curves for cement and concrete resemble those for other brittle materials like cast iron, brick, and stone. Carefully made experiments fail to disclose a limit of proportionality or an elastic limit. Compression tests indicate, however, that after several applications of stresses less than one-half of the ultimate strength of concrete the set becomes momentarily constant. On account of the occurrence of set for low intensities of stress, the true elastic stress-deformation curve for these materials may differ considerably from the gross deformation curve. Bach, in finding the true elastic curve in compression, repeatedly applied and released each load until the set at zero load became constant. By subtracting the set from the total deformation the elastic deformation for a given load was determined. Although the true elastic curve is of importance in considering the change of shape of concrete after removal of stress, the total unit deformation due both to the initial imposition of load and to the further yielding with time are the more important factors in arriving at a measure of stress from strain either in plain or reinforced concrete. The *increase* in unit strain caused by the *sustained* application of a unit stress of unity is called the *plastic flow*. Methods of estimating strains due to sustained stress are given in Art. 520.

519. Calculation of the Modulus of Elasticity.—Since mortar and concrete have no elastic limit, the modulus of elasticity must be the slope of the stress-deformation curve at zero stress. For mixes which have a stress-deformation curve of sharp curvature near the origin, the initial modulus of elasticity, E, is of little value, except for comparing the stiffness of different concretes; since for all finite values of unit stress, S, or unit deformation, ϵ, $E\epsilon > S$ and $\frac{S}{E} < \epsilon$, as may be seen from Fig. 17. For such curves the slope of a secant drawn from the origin through a point corresponding to a working unit stress is useful in determining stresses from strains accompanying momentary working loads. Also, in reinforced concrete design the use of the secant modulus considerably shortens the computations without undue sacrifice of accuracy.

Professor Bach's studies of true elastic curves led to an exponential equation for unit deformation in compression, $\epsilon = KS_c^m$, in which K and

m are constants depending upon the material. Mörsch * gives the following equations of the true elastic curve for 1 : 2½ : 5 sand and gravel con-

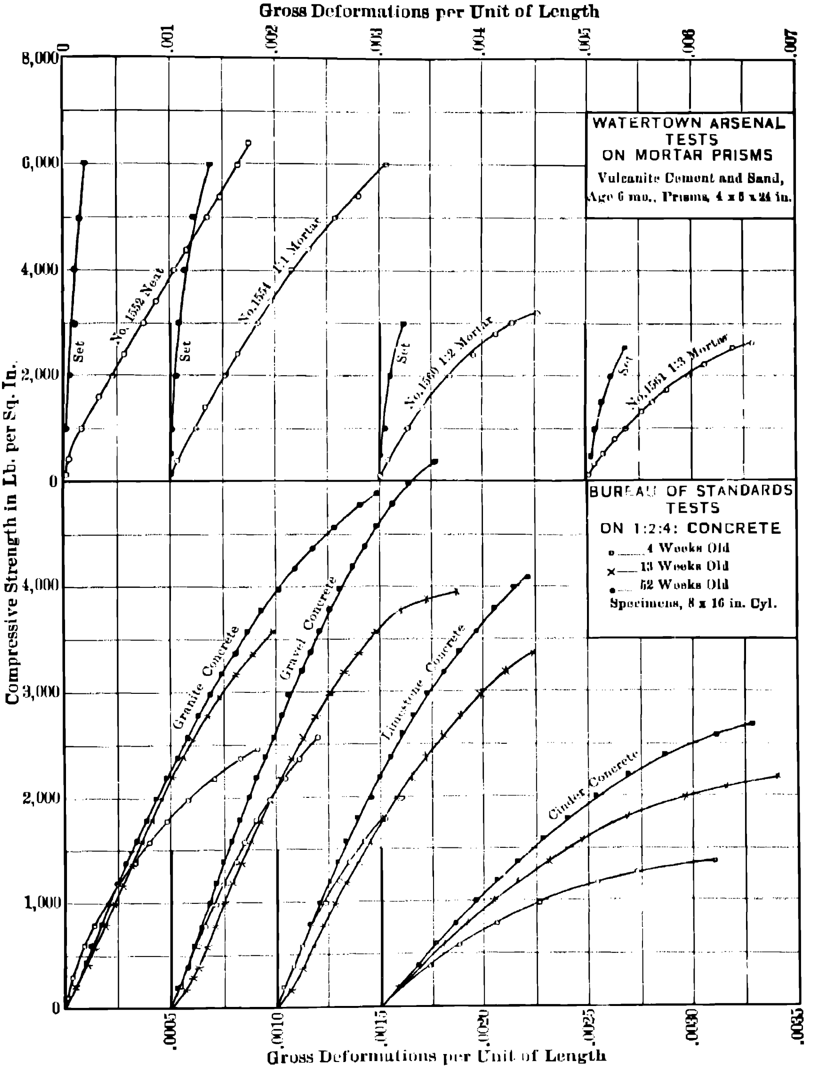

FIG. 16.—Stress-deformation Diagrams for Mortars and Concretes in Compression (*Tests of Metals*, 1904. *Technologic Paper* No. 2.)

crete and 1 : 2½ : 5 sand and broken-stone concrete, $\epsilon=\dfrac{S_c^{1.14}}{5,676,100}$ and $\epsilon=\dfrac{S_c^{1.16}}{9,190,500}$, respectively.

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* *Eisenbetonbau*, p. 22 (trans.).

Prof. Talbot * developed a formula for the elastic curve in compression, based upon the theory that the stress-gross-deformation curve for concrete is a parabola. His formula is $S_c=(1-\frac{1}{2}q)E_c\epsilon$ in which q is the ratio of ϵ (the unit deformation for S_c), to the ultimate unit deformation, and E_c is the initial modulus.

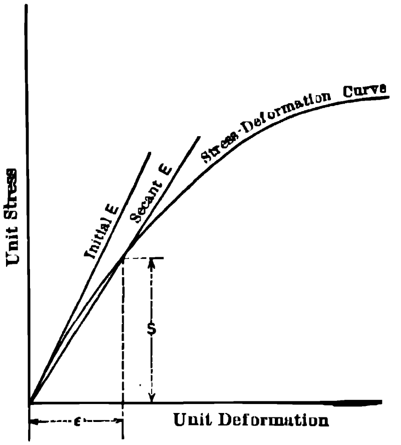

FIG. 17.—Method of Finding the (Secant) Modulus of Elasticity, $E=\frac{S}{\epsilon}$.

520. Values of the Modulus of Elasticity of Mortars and Concretes.—Table 11 shows values of the moduli of elasticity of neat cement, and concretes compiled from the sources mentioned. The modulus increases with the density, and to some extent with age, if specimens are water-cured. Mörsch's results show that the moduli for wet mixes are less than for dry mixes of the same proportions. For lean mixes of the same aggregate, the modulus like the strength increases with the proportion of cement; but the variation is small for proportions richer than 1 : 2, in the case of mortar, or 1 : $1\frac{1}{2}$: 3, in the case of concrete.

The stiffness of the aggregate affects both the elasticity and the strength of concrete. Large differences between the stiffness of the mortar and aggregate must promote non-uniformity of stress under load and undoubtedly account for the low early strengths of concretes made from certain granites and trap rocks.

From 3500 tests of concrete in which mix, grading, water ratio, and type of aggregate were variables, Walker concluded that the initial modulus of elasticity (E_i) and the tangent modulus at $\frac{1}{4}$ ultimate (E_{25}) varied within limits with the compressive strength (S_c) thus: $E_i = 33{,}000\ S_c^{\frac{5}{8}}$ and $E_{25} = 66{,}000\ S_c^{\frac{1}{2}}$.

In *Bulletin* 90, Engr. Expt. Sta., Ames, Iowa, J. W. Johnson reports 750 tests on modulus of elasticity in tension and in compression. His data indicate that the modulus in tension is in most cases slightly less than in compression but for design purposes they may be considered equal.

Plastic Flow.—From the studies of J. R. Shank † it appears that for ordinary concrete of Portland cement and common aggregates loaded in air at 28 days, the plastic flow (y) in millionths (in./in.) per 1 lb./in.^{2} is approximated by $y = 0.13x^{\frac{1}{3}}$, where x is the time the load is sustained in

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* *Bull.* No. 14, Engr. Expt. Sta., Univ. of Ill.

† *Proc. Am. Conc. Inst.*, Vol. 32, p. 149; also Vol. 33, p. 123.

TABLE 11.—MODULI OF ELASTICITY FOR NEAT CEMENT, MORTAR AND CONCRETE

No. Spec.	Mix, by Volume	Age, in Months	Method of Curing	Consistency	Aggregate	Dimensions of Spec., in Inches	Modulus of Elasticity, Pounds per Square Inch		Range of Stress (Lb./In.^{2})	Authority
							Tension	Compression		
3	1 : 1.8 : 1.2	3	....	Dry	Sand and Gravel <0.8 in.	7×7×29	3,380,000	3,650,000	0–552 C. 0–44 T. elastic def.	Mörsch
				Wet			2,950,000	3,160,000		
3	1 : 2.4 : 1.6	3	....	Dry			3,410,000	3,200,000		
				Wet			3,140,000	2,630,000		
21	1 : 2 : 4	1	Moist Air	Medium	Sand and Cinders	8×16 in. cyl.	....	1,610,000	Initial E	Bureau of St'ds *Tech. Paper* No. 2
21	1 : 2 : 4	12						2,110,000		
21	1 : 2 : 4	1			Sand and Granite	8×16 in. cyl.	....	4,290,000		
21	1 : 2 : 4	12						4,770,000		
21	1 : 2 : 4	1			Sand and Gravel	8×16 in. cyl.	....	4,600,000		
21	1 : 2 : 4	12						5,390,000		
21	1 : 2 : 4	1			Sand and Limestone	8×16 in. cyl.	....	3,590,000		
21	1 : 2 : 4	12						4,550,000		
5	Neat	1	Moist Air	Flow200	Sand and Gravel <1½ in.	6×12-in. cyl.	....	2,510,000	Secant 0 to ¼ Ult.	Walker, *Bull. No.* 5 Structural Materials Research Laboratory
	1 : 0.3 : 0.8							3,150,000		
	1 : 0.7 : 1.6							4,500,000		
	1 : 1.0 : 2.8							4,510,000		
	1 : 1.4 : 3.2							4,120,000		
	1 : 1.7 : 4.0							4,310,000		
	1 : 2.4 : 5.7							4,030,000		
	By Weight				Sd. + Gl.	Cylinders	Comp. Str.			
13	1 : 2.4 : 7.0	1	Moist Air	3-in. Sl.	< 9 in.	36×72 in.	3090	5,100,000	Initial E	Boulder Dam Bureau of Reclamation *Proc. A.C.I.*, Vol.31, p.280
14	1 : 2.4 : 6.4	1		3-in. Sl.	< 6 in.	24×48 in.	3020	5,200,000		
6	1 : 2.5 : 4.9	1		3¾-in. Sl.	< 3 in.	24×48 in.	3250	5,100,000		
9	1 : 2.4 : 3.3	1		5-in. Sl.	<1½ in.	24×48 in.	3400	4,720,000		
155	1 : 2.4 : 3.3	1		5-in. Sl.	<1½ in.	6×12 in.	4050	5,400,000		

days up to 1 year. For maximum effect due to sustained load, increase the value at 1 year by 27 per cent. For similar concretes in water the plastic flow is about half as much; the equation is $y = 0.089x^{\frac{1}{4}}$. Hence the effective value of the modulus of elasticity (E_y) for calculation of stresses may be approximated for a sustained load by $E_y = E_c/(1 + E_c y)$, in which y would be calculated for the duration of the load. In the present state of our knowledge, for ordinary concretes in air under usual working stresses of long duration, E_y will not be far from 1,000,000 lb./in.^{2}, and 1,500,000 lb./in.^{2} for strong lean vibrated concrete.

521. Poisson's Ratio for Concrete.—Under compression the unit lateral expansion of concrete is about one-sixth to one-twelfth of the unit strain in the direction of the applied forces for the ordinary range of working stress. The ratio increases with the richness of the mix and is influenced by the other factors which affect the magnitude of the modulus of elasticity. Values of Poisson's ratio in compression found by Talbot (*Bull.* No. 20, Univ. of Illinois) varies between 0.1 and 0.16 for working loads on 1 : 2 : 4 concrete sixty days old. Withey (*Bull.* No. 466, Univ. of Wisconsin) found, for stresses at one-fourth of the ultimate strength on concrete two months old, the following values: For 1 : 3 : 6 mix, 0.08; for 1 : 2 : 4 mix, 0.11; for 1 : $1\frac{3}{4}$: $3\frac{1}{4}$ mix, 0.18; for 1 : $1\frac{1}{3}$ mortar, 0.16.

522. Expansion and Shrinkage Due to Variations in Moisture Content.*—Concrete will shrink upon drying and expand upon wetting, independent of any changes due to temperature or load. Shrinkage may take place from the beginning while the mass is still plastic and will continue until the concrete is thoroughly dry.

The behavior during the plastic state is the same as that of any inert powdered material mixed with water, the shrinkage that develops being a consolidation of the mass which takes place as water is lost.

Shrinkage during the hardened state occurs chiefly in the cement paste and depends upon the amount of paste in the mix and the quantity of water lost.

Shrinkage during the plastic state can be obviated by preventing the loss of water from the mass, either through evaporation from the surface or through absorption of water by the aggregates, forms, or other media. Shrinkage during the hardened state can be kept to a minimum by the proper selection of the mix.

The relationship between the quantity of water lost, the cement content of the mix and the shrinkage, is shown in the lower diagram of Fig. 18. The relationship between quantity of water lost and the water-cement ratio is shown by the upper diagram. These diagrams are based on tests which included concretes and mortars, using sand and gravel aggregates, with the cement content varying from 3 to 15 sacks per cubic yard. The specimens were 5 × 5 × 17 inches, and all the mixes were workable. The curing consisted of an initial period of 7 days in the moist room followed by 6 months in air at 70° F. and 50 per cent relative humidity. This condition of curing resulted in almost complete drying, as was shown by forced drying in an oven at 120° F. at the end of this period, which produced very little additional loss in weight. The diagram therefore represents about the maximum shrinkage that may be expected.

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* Prepared by M. B. Lagaard from tests conducted in the Research Laboratory of the Portland Cement Association.

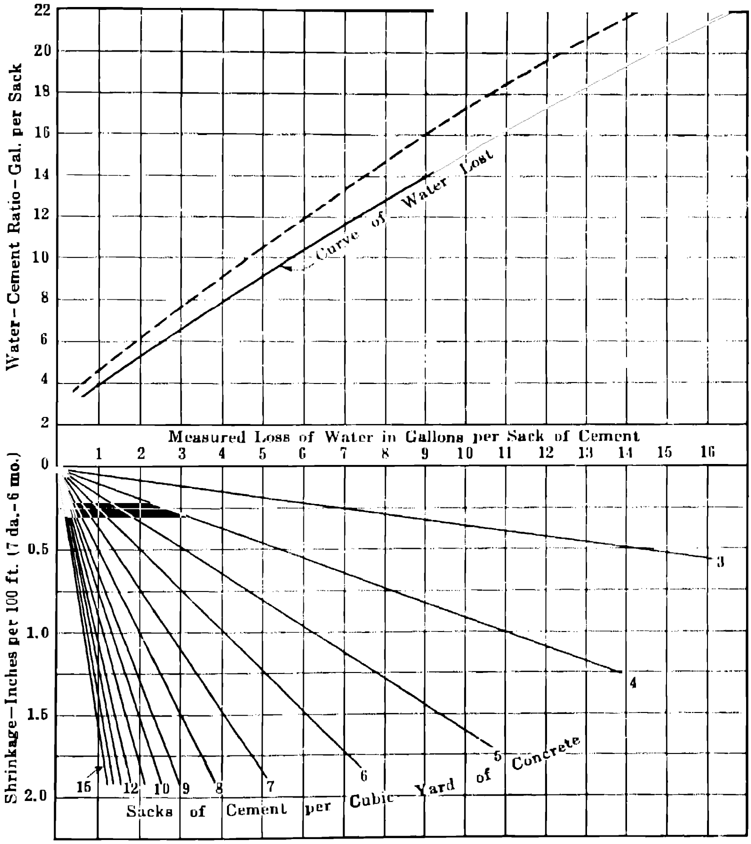


FIG. 18.—Interrelationship of Shrinkage, Loss in Weight, Cement Content and Water-Cement Ratio (Lagaard).

To use the diagram in predicting the shrinkage of any mix for these conditions, determine the water-cement ratio and the number of sacks of cement in a cubic yard of concrete. From a point on the upper curve, representing the water-cement ratio, proceed vertically to the radiating line in the lower diagram representing the number of sacks of cement in a cubic yard of concrete. The shrinkage can then be read directly from the scale at the left.

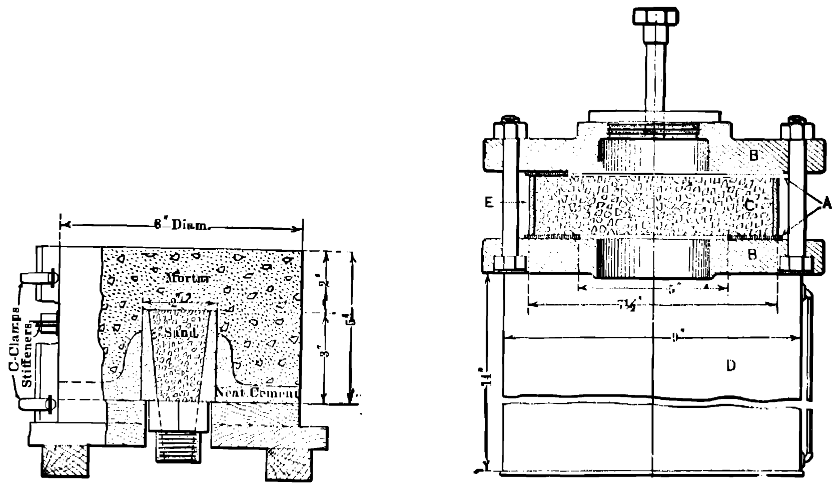
For other conditions of exposure, it will be necessary to estimate the probable position of the curve of water lost for the expected condition of drying, and determine the shrinkage on the basis of the new curve. The dotted curve shows the water lost from these same specimens at the age of 28 days, representing 1 week in the moist room and 3 weeks in air at 50 per cent relative humidity and 70° F. This will help in estimating the probable position of the curve of water lost for other conditions, but consideration must be given to the mass of concrete involved and the opportunity for drying out. The shrinkage in larger masses in outdoor exposure may be as little as $\frac{1}{3}$ the maximum values determined from the diagram. In thin sections, subject to the direct rays of the sun or in artificially heated buildings, the maximum possible shrinkage indicated by these curves may be developed.

THE PERMEABILITY AND ABSORPTION OF MORTAR AND CONCRETE

523. Discussion of Terms.—Water may enter a porous body through capillary attraction, it may be forced in under pressure, or it may be introduced by a combination of pressure and capillary attraction. The character and size of the minute canals connecting the pores with one another and with the exterior of the body are apparently the factors which determine the rate of flow into the body. By absorption is meant the drawing in of water by capillary attraction. All cement mixtures absorb water to some extent. When the size and arrangement of the canals are such as to permit water to flow through the substance it is said to be permeable. The rate of absorption is dependent upon the size, number of pores connected with the surface of the body, and upon the size and character of the connecting ducts; the permeability is dependent upon the character and size of the minute passageways leading through the body, consequently there can be no relation between these properties.

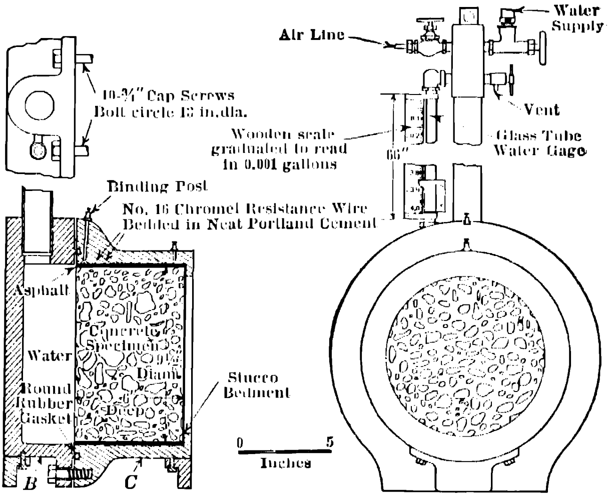
With hydrostatic heads of 100 ft., tests have been made which indicate that neither Portland cement paste nor mixtures made from it are absolutely impervious. Nevertheless, there is abundant evidence which shows that concrete and mortar can be made so impermeable that no leakage or dampness is visible on the surface opposite to the water pressure. Apparently, even when the humidity is high, the frictional resistance to flow prevents the water from leaving the free surface of such material at a rapid enough rate to escape evaporation. Concrete or mortar similar to the above will hereafter be frequently referred to as impermeable or impervious. The approximation in such statement should be remembered.

524. Objectives and Methods of Testing Permeability.—Although the principal objective in permeability testing is to find the water tightness of the concrete, such tests often have little direct relation to the imper-



(*a*) Sectional Elevation of Mortar Permeability Specimen, not Suitable for Concrete. (University of Wisconsin).

(*b*) Sectional Elevation of Bureau of Standards' Specimen. (*AA* = rubber washers; *BB* = cast-iron top and bottom of holder; *C* = specimen; *D* = retainer for leakage; *E* = wrought-iron pipe.)



(c) Specimen Used for Testing Permeability of Concrete to Water at the University of Wisconsin.

FIG. 19.—TYPES OF PERMEABILITY SPECIMENS.

viousness of the structure due to presence of cracks and poor joints. On the other hand, the test is useful in determining the corrosive effects of percolating waters which leach out the free lime and gradually attack the lime in the tricalcium silicate. It can also be used to measure the relative efficiencies of cements and their rates of hydration.

Two methods of measuring permeability are in use. In one, the water passing out of the specimen is measured; in the other, the quantity entering is determined. The first method does not require as elaborate apparatus as the second, but is inaccurate when the leakage is small due to evaporation losses. The second method necessitates the use of a calibrated water gage for measuring the flow and air pressure to force the water into the specimens. Corrections due to temperature changes are also necessary when the flows are small. Measurements made by the latter method may include both the water absorbed and the water passing through the specimen, depending on the method of curing.

Figure 19 shows three forms of specimen which, more or less modified, have been used in many important experiments. The type illustrated in Fig. 19*a* is the simplest, most easily made and readily attached to the testing apparatus; but the path of flow is neither restricted to a definite volume of concrete, nor is the area of the opening in the casting sufficient for the testing of concrete made from large aggregate.

Figure 19*b* illustrates the form of mortar test-piece used by the Bureau of Standards. Similar specimens 18 in. in diameter were used in testing concrete. This type of test-piece requires expensive castings and gaskets. If the flow into the specimen is to be measured, it is probable that difficulty in securing a tight joint at the gasketed surfaces will be experienced when high pressures are used.

The specimen shown in Fig. 19*c* has been successfully used in many tests at the University of Wisconsin. In the form shown, the cross-section exposed to pressure is ½ sq. ft. in area and the volume is ¼ cu. ft. Curing conditions may be varied and tests repeated at different time intervals on the same specimen. Specimens are cast in simple cylindrical molds cured as desired; then, with part *C* rotated 90° to the right of position shown, they are bedded in neat gypsum on the circular shelf of the casting. After the plaster has dried for a half hour, the ⅜-in. annular space around the specimen is filled with Crystal Steep Roofing Asphalt. The bonnet, *B*, is then bolted to the casting, the tube filled with water, and pressure up to 100 lb./in.^{2} can be applied by means of an automatically controlled air pump. Readings of flow into the apparatus are taken at regular time intervals on the water gage and leakage from the face of the specimen noted. The resistance wire is used to heat the casting during the sealing process and in releasing the specimen after test.

In the tests for Boulder Dam, the Bureau of Reclamation engineers adopted an 18 by 18-in. cylindrical specimen, which was sealed with axis vertical in a manner similar to that shown in Fig. 19*c*, and pressures up to 400 lb./in.^{2} were applied.

In making permeability specimens, homogeneity is a prime requisite. Laitance and excess mortar should be removed by a wire brush from the faces of specimens within 24 hr. after casting. Molds must be water-tight. Care must be exercised to insure water-tight seals in testing.

525. The Effect of the Proportion of Cement on Permeability.—Data from tests show that the flow through concrete or mortar decreases with the increase in proportion of cement provided the density is constant. Plastic neat cement and 1 : 1 mortar linings 2 in. or over in thickness may be considered impervious under heads less than 100 ft., provided the mortar is not cracked by overstressing. If made of bank sands of good quality, 1 : 2 mortars of plastic consistency will, in general, show no leakage under a like pressure. With well-graded sands impervious mortars of 1 : 3 and 1 : 4 proportions may be secured. Fig. 20 (*Proc. A.S.T.M.*, Vol. 13, p. 835) well shows the effect of the proportion of cement upon the permeability of mortars made of fine (*Sd* 4), medium (*Sd* 8), and coarse (*Sd* 9) sands. The experiments were made on specimens like Fig. 19*a*. The properties of these sands may be found in Table 5, Ch. XIII.

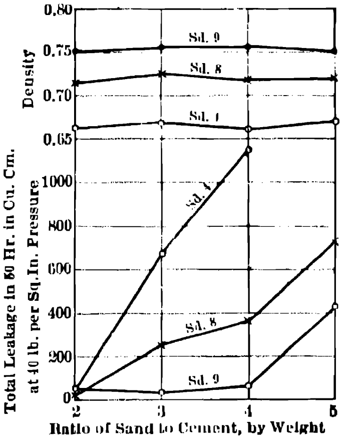


FIG. 20.—The Influence of Proportion of Cement on the Permeability of Mortar Made from Fine (*Sd* 4), Medium (*Sd* 8), and Coarse (*Sd* 9) Sands.

Extensive tests at the University of Wisconsin are reported in *Trans. Wes. Soc. Engr.*, Vol. 19, p. 833; *Engineering Bulletin* No. 1245; *Engr. Reprint* No. 22 and 41. These data show that hand-puddled concrete made with well-graded gravel or broken stone less than 1½-in. in size, and with a slump of 2 to 4 in., can be made impermeable to heads under 100 ft. by using 5½ to 7 sacks of cement per cu. yd., provided the thickness is 1 ft. or more. For heads of 10 ft. or less, properly made mixes with 4 sacks per cu. yd. can be made water-tight. By using mixes of 0 to ½-in. slump and internal vibration in placing, mixes can be made water-tight under 100 ft. head with only 4 sacks of cement per cu. yd.

526. Effects of Density and Water-Cement Ratio on Permeability.—With the same cement content the permeability of concrete or mortar increases as the density decreases. This is most marked in lean mixes.

From the results of numerous tests on sand mortars, R. Feret concluded that most impermeable mortar for any given proportion of cement will be obtained when the percentage of fine sand (*F*) plus cement equals the percentage of coarse sand (*G*). This grading, he also found, produced the maximum strength and density (see Art. 502). Mortars made from fine sand he found more impervious than those containing large grains (*G*) only.

Figure 21 shows the relation of leakage to the cement-void ratio for certain of the Wisconsin mortar and gravel concrete tests. Figure 21 (*a*) and (*b*) indicate the effect of the cement-void ratio on the leakage of the leaner mortars and concretes. Figure 21 (*b*) illustrates the superior water-tightness of the 0-slump concrete specimens 6 in. thick placed by vibration to that of the 2 to 4-in. slump, hand-puddled mixes. None of the specimens with flows of 0.0005 gal./sq. ft./hr., or less, exhibited visible leakage. Water-tightness, as measured by invisible leakage under a 100-ft. head for a thickness of 1 ft., is indicated as obtainable for mixes with $w/c = 0.5$, or less, by weight, in Fig. 21(*c*) and in Fig. 3, Ch. X. These diagrams also indicate the superior water-tightness of the concretes made of the finely ground, high-early-strength cements and the Portland-puzzolan cement.

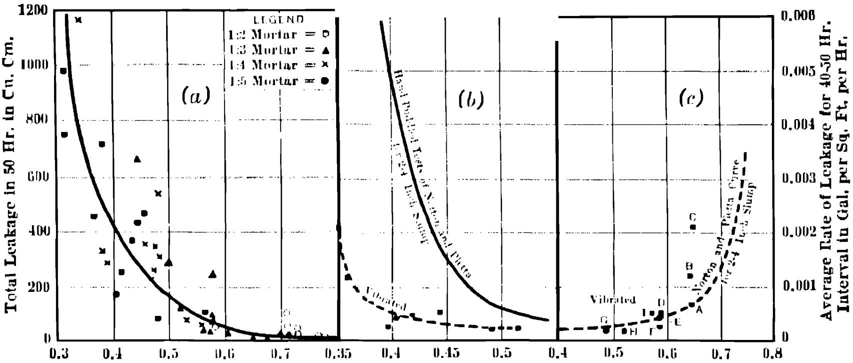


FIG. 21.—Relation of Leakage to (*a*) Cement-Void Ratio for Mortars, (*b*) Cement-Void Ratio for Concrete, (*c*) Water-Cement Ratio for Concrete. Pressure, 40 lb./in.^{2}

For hand-puddled concrete made of gravel under 1½ in. in size and a good sand, $m = 2.7$, Norton and Pletta's tests at Wisconsin show that the highest degree of water-tightness was obtained with the mixed aggregate graded to *m*-values of 5.2, 5.5, and 5.8 for the 1 : 4, 1 : 5, and 1 : 6 mixes, by volume, respectively. For the vibrated mixes made of the same aggregates, Fig. 21(*b*), the values of *m* ranged from 5.7 to 5.9, and the cement contents from 2.9 to 3.8 sacks per cu. yd. For the 2.9-sack mixes represented by points *A*, *B*, and *C*, the sand to gravel ratios were 0.30, 0.32, and 0.34 and the values of *m*, 5.9, 5.8, and 5.7. These data all indicate the pronounced influence of grading on the density and water-tightness of lean mixes.

527. The Effect of Consistency on Permeability.—With hand placing, a dry mix leads to pin holes and heavy leakages, especially with lean concretes. The use of excess water reduces density and increases flow. A slight excess of water produces far less leakage than a similar deficiency, even in a mix as rich as 1 : 1½ : 3. For most hand-placed concrete, the minimum slump which can be successfully used varies from 2 to 6 in., depending upon the richness of the mix, size of aggregate, intricacy of reinforcing, width of forms, and amount of puddling. With vibrated concrete, slumps of 0 to 1 in. can often be used effectively on massive constructions, and rarely need the slump exceed 2 in.

528. Permeability Coefficients.—From the high-pressure permeability tests of the Bureau of Reclamation * in connection with Boulder and other dams, A. Ruettgers, E. N. Vidal, and S. P. Wing established several useful coefficients based on the application of D'Arcy's Law, $Q/A_c = K_c H/L$, to flow of water through concrete. By repeatedly testing specimens under different pressures and other specimens differing in thickness, they demonstrated that the quantity of water (Q) flowing in a given time was proportional to the ratio of the head (H) to the percolation length, or thickness of specimen, (L). Hence the *permeability coefficient* (K_c) represents the unit rate of discharge in cubic feet per second due to a head of one foot acting on a specimen of one square foot cross-section and one foot thick.

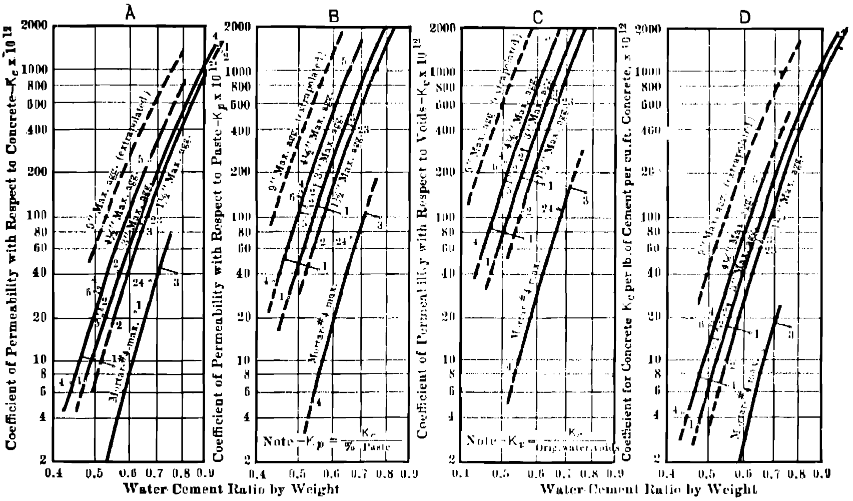


FIG. 22.—Coefficients of Permeability of Concrete.
(*Proc. Am. Conc. Inst.*, Vol. 31, p. 395.)

From their tests using measured rates of inflow after flows of 250 hours or more, and their studies of existing data, they evolved the diagrams shown in Fig. 22. In Fig. 22*a*, K_c has the aforesaid significance.

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* *Proc. Am. Conc. Inst.*, Vol. 31, p. 382; Vol. 32, p. 230, p. 378.

Dividing K_c by the absolute volume of the paste in the mix, the equivalent of $1-s-g$, gives the coefficient K_p. By comparing values of K_p found by different experimenters for the same w/c ratios, a measure of the corrosive action of the percolating water can be had.

The Density Coefficient.—Dividing K_c by the volume of mixing water per unit volume of concrete furnished the coefficient K_v. K_v is directly proportional to the mean velocity of the percolating water and is a more sensitive measure than K_c of the influence of the water-cement ratio and coarseness of the aggregate on the pore formation.

The Corrosion Coefficient.—The coefficient K_c per pound of cement per cubic foot of concrete is a direct measure of the relative life of the concrete, since it measures the rate of corrosion due to percolating water.

These experimenters also furnished evidence to show that there was little effect on strength due to a removal of 20 per cent of the lime content by corrosive action of the percolating water, but a removal of 33 per cent entailed an 11 per cent strength loss. In order to produce a removal of half the lime they estimated that a percolation of 35 cu. ft. of water would be required for each pound of cement in the concrete mass, assuming water as corrosive as distilled water.

In addition to the foregoing, the Bureau's tests indicated that the major factors affecting the permeability of their vibrated gravel concrete of 2 to 4-in. slump was the water-cement ratio and the maximum size of aggregate (Fig. 22). Their analysis indicates that water percolated through (*a*) inter-sand voids above the settled cement paste which increased rapidly in size for values of the water-cement ratio greater than 0.4 to 0.5, by weight; (*b*) minute voids in the cement paste which depended for size upon the state of the chemical reaction; and (*c*) voids under the coarse aggregate particles, caused by settlement of the mortar and depending upon the size of the aggregate and the water-cement ratio. Tests on neat cement pastes furnished higher K_c and K_p values than concretes with ½-in. aggregate or mortars. This shows that the water-tightness of the neat paste is improved by additions of properly graded aggregates which break up interconnected pores in the paste.

Their tests indicated that Boulder Dam mass concrete containing 9-in. gravel and 1 barrel of low-heat cement per cu. yd. is so impermeable that the flow through its pore structure is negligible.

In this very informative report are also included permeability coefficients and classes of permeability for various materials as listed in Table 12. An increase in the classification number of unity indicates an increase in impermeability of ten times.

529. Effect of Curing on Permeability.—Proper curing is of the utmost importance if impermeable concrete or mortar is to be secured. Premature drying adversely affects the imperviousness of lean mixes

TABLE 12.—TABULATION OF TYPICAL PERMEABILITY COEFFICIENTS FOR VARYING MATERIALS

Coefficient represents quantity of water in cubic feet per second, per square foot of surface exposed to percolation, passing through one foot of substance with one foot head. $Q = \frac{K_r H}{L}$

Material	$K \times 10^{12}$	Class
Granite specimen	2—10	12
Slate specimen	3—7	12
CONCRETE and MORTAR, w/c 0.5—0.6	1—300	12—10
Breccia specimen	20—	11
CONCRETE and MORTAR, w/c 0.6—0.7	10—650	11—10
Calcite specimen	20—400	11—10
CONCRETE and MORTAR, w/c 0.7—0.8	30—1,400	11—9
Limestone specimen	30—50,000	11—8
CONCRETE and MORTAR, w/c 0.8—1.0	150—2,500	10—9
Dolomite specimen	200—500	10
CONCRETE and MORTAR, w/c 1.2—2.0	1,000—70,000	9—8
Biotite gneiss in place, field test	1,000—100,000	9—7
Sandstone specimen	7,000—500,000	9—7
Cores for earth dams	1,000—1,000,000	9—6
Slate in place, field test	10,000—1,000,000	8—6
Face brick	100,000—1,000,000	7—6
CONCRETE, unreinforced canal linings, field test	100,000—2,000,000	7—6
*Steel sheet piling—junction open 1/1000″ with ¼″ of contact—18″ sections	500,000—	7
*CONCRETE, restrained slabs with ¼ to ½% reinforcing—30° Temp. change	1,000,000—5,000,000	6
Water bearing sands	1,000,000,000	3

* Flow through 1 ft. length of crack, 1 ft. deep, $Q = 60{,}000 \frac{H}{L} D^3$

much more than that of the rich mixes. The imperviousness of lean mixtures properly cured for three weeks may be entirely destroyed by drying at 120 to 150° F. These facts are evident from the previously mentioned tests at Wisconsin. Also the increase in percolation is roughly in proportion to the weight lost in drying. The Bureau of Reclamation tests show that the percentage of percolation after various lengths of moist curing varied as follows: after 20 days 300, 30 days 200, 60 days 100, 270 days 50 per cent. These influences are more important in structures under 6 in. or a foot in thickness, since atmospheric drying causes little moisture withdrawal beyond a depth of 2 or 3 in. from the surface.

530. Other Conditions Affecting Permeability.—The water-tightness of concrete will also vary with the fineness of the cement, the character of the aggregate, the quality of the percolating water, time of mixing, and to some extent with the direction of flow.

The influence of fineness of cement is evident in the data of Fig. 3, Ch. X. With hand placement, angular or flat particles of aggregate are less easily compacted than rounded particles.

The water-tightness of the concrete will also be affected by the porosity of the aggregate. A rapid flow is likely to increase with water of high *p*H content due to a more rapid leaching of the lime from the cement and to decrease if the percolating water contains sediment or bacteria which will plug the pores of the concrete. A low flow may gradually diminish due to the deposition of lime carbonate in the pores of the concrete.

The Wisconsin tests showed that the amount of mixing markedly influenced the water-tightness of hand-puddled lean mixes such as 1 : 9, by weight, but affected the water-tightness of the rich mixes much less.

With hand-puddled concrete the Wisconsin tests showed greater permeability when the pressure was normal to the direction of pouring than when parallel to that direction. In the Bureau of Reclamation tests on vibrated concrete the percolation was the same in either direction.

531. The Absorption of Concrete and Mortar.—A proper method of testing the absorptive properties of concrete or mortar is yet to be determined. By drying these substances at temperatures above 120 to 150° F. the imperviousness is greatly reduced, and consequently water will penetrate farther into such material than it would into undried concrete. Nevertheless, the method of conducting the absorption test ordinarily employed for other porous materials is generally used in testing mortar and concrete.

A series of tests on the absorption of 1 : 2, 1 : 4, 1 : 6 and 1 : 8 mortars made from three different sands is reported in *Technologic Paper* No. 2. The test-pieces were 2-in. cubes. They were stored in a damp room between testing periods. Before testing they were dried for several days at a temperature of 212 to 230° F. After cooling they were immersed in water to a depth of 3 in. They were periodically weighed until they gained less than $\frac{1}{20}$ of 1 per cent per day; the test was then stopped.

The experiments show that the absorption generally decreases with age, the greatest change occurring in the first two months. Mortars of damp consistency absorbed more than those of quaking consistency. Mortars made of coarse sand were somewhat less absorptive than those made of fine sands. The absorption, in general, decreased with the increase in richness of mix. The results show, however, that some factor, probably porosity, exercised a more important influence than the proportion of cement. Slag sand mortars, on account of the porosity of the aggregate, absorbed much more water than either the fine or coarse sand mortars.

Absorption tests made at the University of Wisconsin on mortars varying in richness from 1 : 2 to 1 : 5 have shown that those made from screenings and find sands generally absorb more water than those made of better graded material. Mortars of 1 : 2 to 1 : 4 proportions made of good materials and properly cured ought not absorb more than 10 per cent of water after forty-eight hours' immersion. Well-made concrete of dense aggregate should not absorb more than 6 per cent of water under the same conditions.

532. Waterproofing Materials.—For a number of years attempts have been made to discover washes and compounds which will waterproof concrete and mortar. In general, tests seem to show that if proper attention is given to a proportioning, mixing, and curing these compounds are not needed to secure impermeable concrete for heads under 100 ft. Furthermore, if good materials are procurable at average prices it is questionable if the extra expense involved in the use of such compounds will not be greater than the cost of additional cement required for water-tightness. It must also be understood that any beneficial results accruing from the use of these compounds cannot offset poor workmanship or improper curing. Furthermore, if the concrete cracks neither a properly made mix nor the use of such washes or compounds are effective. When there is probability of cracking, expansion joints should be used or a waterproof elastic membrane forming an integral part of the wall should be employed.

Waterproofing compounds may be divided into two classes: integral mixtures, those which are added before the concrete is mixed; and surface washes, those which are applied after the work is finished. The integral mixtures may be inert, simply void fillers such as finely ground clay or hydrated lime; or they may be active by virtue of compounds which they form during the hardening of the cement or by their repelling action toward water, the soap and alum combination, for example. The coatings comprise seven classes. These are: 1, water solutions of inorganic salts, such as magnesium fluosilicate, zinc sulphate, and sodium silicate; 2, water suspensions of pore-filling substances, such as iron filings or casein in ammonia; 3, soap solutions with an evaporable solvent which react with the hydrated lime to fill the pores; 4, combinations of solutions in successive applications which react chemically and fill the pores, such as the soap and alum process and the sodium-sulphate, barium-chloride combination; 5, solutions of solid hydrocarbons in oil or paraffin, such as Minwax; 6, bituminous coatings such as the Asphalt emulsions; and 7, miscellaneous, such as cement and mortar grouts. For reports on surface coatings, see *Proc. Am. Conc. Inst.*, Vol. 28, p. 209, and Vol. 30, p. 1.

533. Effect of Hydrated Lime on Permeability.—On account of the plasticity and easy working qualities which hydrated lime imparts to cement mortars, and since it also decreases segregation, it has been considerably used as a waterproofing compound. It may be mixed with the cement in proportions less than 15 per cent without producing loss in strength of concrete. Numerous tests on mortars and concretes have indicated that its use decreased permeability.* With a 60-lb. per square inch water pressure, S. E. Thompson's tests * indicated that additions of 8, 12 and 16 per cent of hydrated lime in terms of the weight of the cement gave water-tight concrete for 1 : 2 : 4, 1 : 2½ : 4½, 1 : 3 : 5 proportions, respectively. The concrete was made of run-of-crusher hard conglomerate rock below 2 in. with dust removed. All of the sand passed a ¼-in. mesh,

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* *Proc. A. S. T. M.*, Vol. 8, p. 500.

26 per cent passed a No. 40 sieve and 4 per cent passed No. 100 sieve. Specimens of the type shown in Fig. 19*a* were used, the thickness of wall subjected to flow was 8 in., and leakage through the specimens was caught and weighed. Thompson contended that hydrated lime paste is a more efficient void filler than Portland cement paste, since the volume of the former is about 2¼ times that of the latter.

Tests of lean concrete made by J. L. Davies * on cylinders 8 in. long, 6 in. in diameter, showed that the rate of flow was decreased by replacing 20 per cent of the cement, by weight, with high calcium lime. The results with dolomitic lime were not so satisfactory. Davies used mixtures varying from 1.1 : 3 : 6 to 1.3 : 3 : 6 by weight and pressures of 40 and 80 lb. per square inch. From a study of his results and the cost per cubic yard of the different concretes based on New York City prices, it does not appear that such use of lime is economical.

Tests by E. W. Lazell † and by the U. S. Bureau of Standards ‡ show that the replacement of 10 per cent of the cement with hydrated lime increases the imperviousness of 1 : 3 and 1 : 4 mortars.

534. Effect of Finely Ground Clay on Permeability of Mortars.—R. H. Gaines § made a number of tests on 1 : 3 mortars in which he replaced 10 per cent of Cowe Bay sand with finely ground clay. Under pressures of 80 lb. per square inch he found no leakage for test-pieces containing the clay, although the normal specimens leaked considerably. Davies also made tests on the efficiency of finely ground clay for waterproofing concrete, but he concluded that this method also was not economical.

535. Integral Mixtures of Alum and Soap.—In experiments at the University of Illinois ‖ on 1 : 6 mortar under 40 to 45 lb. per square inch pressure the permeability was greatly reduced by the use of a soap and alum mixture amounting to 1.2 per cent of the cement. The experimenters recommended a 1 : 3 mixture of alum sulphate and hard soap. Compressive tests showed a small reduction in the strength of the mix due to the alum content. The lasting qualities of such treatment are, however, to be questioned.

536. Waterproofing by Surface Washes.—Between 1924 and 1933 tests on the waterproofing efficiency of 21 surface washes covering the 7 classes enumerated were made at the University of Wisconsin by C. L. Neumeister and G. W. Washa. The specimens were of the type shown in Fig. 19(*c*). Specimens initially permeable were chosen and their flows determined immediately prior to treatment under a pressure of 40 lb./in.^{2}

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* *Engr. News*, Vol. 68, p. 866.

† *Proc. A. S. T. M.*, Vol. 6, p. 341.

‡ *Technologic Paper* No. 3, by R. J. Wig and P. H. Bates.

§ *Engr. News*, Sept. 26, 1907.

‖ *Engr. News*, Vol. 62, p. 390.

over the 40 to 50-hr. interval. They were then treated with a surface wash in accordance with the recommended procedure and again tested for flow. The efficiency of a treatment was based on the ratio of the difference between flow before and after treatment to the initial flow. The efficiency for a given wash was calculated from 3 or 4 such tests.

Of the washes in the first six classes, Colorless Minwax had the highest efficiency, 72 per cent. After a 2-year exposure out of doors it exhibited an efficiency of 44 per cent. Four coats of asphalt emulsion had an efficiency of 71 per cent, but it was not available at the time the exposure tests were run. This material is very easy to apply. Most of the washes showed severe losses in efficiency due to the 2-year exposure.

Neat cement and 1 : 1 and 1 : 2 grouts containing sand passing a No. 20 sieve were also tested. Three coats of each of these washes were applied at intervals of 10 to 12 hr. After this they were kept moist under damp burlap for various lengths of time up to 7 days. The efficiency of the washes improved with the length of the curing period, and there was a marked increase in the efficiency of the specimens cured 7 days as compared to those cured only 3 days. The 1 : 1 grout exhibited an efficiency of 88 per cent and the lowest flow after treatment of any of the washes tested. The 1 : 2 grout was next with an efficiency of 72 per cent. The efficiency of the neat cement wash was only 65 per cent. None of these cement washes were run in the exposure tests.

537. Waterproof Membranes.—Absolute imperviousness can be secured by the use of several layers of fabric like the better grades of roofing felt cemented to the work by hot asphalt or coal tar washes. To prevent deterioration it is well to cover the alternate layers of pitch and felt with a protective layer of concrete or mortar.*

538. Surface Hardeners.—The surface of an improperly cured floor can be hardened and rendered less dusty by the application of water solutions of either aluminum sulphate or sodium silicate. Prior to either treatment the floor must be thoroughly cleaned, scrubbed, and allowed to dry completely.

If aluminum sulphate is used, a 15 per cent solution should be prepared a few days in advance of treatment in order to dissolve the sulphate completely. The quantity required may be estimated at 1 gal. per 100 sq. ft. Apply 3 coats with a mop or soft brush at 24-hr. intervals, allowing each to dry thoroughly.

If commercial sodium silicate is applied, it should be thinned with 4 times its weight of water. One gallon of this solution will cover about

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* For further information concerning methods of waterproofing concrete, see *Proc. American Concrete Institute*, Vol. 19, p. 294, and Vol. 20, p. 641.

Results of tests on concrete waterproofed by fabrics may be found in *Bulletin* No. 336 of The University of Wisconsin.

200 sq. ft. Three applications should be made, and each one should be thoroughly brushed into the surface for several minutes. After each coat has dried it should be carefully washed and again dried before the next application is made.

THE EFFECTS OF TEMPERATURE ON MORTAR AND CONCRETE

539. The Effects of Low Temperatures on the Hardening of Concrete.— An extensive investigation of the effects of low temperatures on the strengths of concrete made with normal and with high-early-strength Portland cements at the Portland Cement Association Laboratory was reported by A. G. Timms and N. H. Withey in *Proc. Am. Conc. Inst.*, Vol. 30, p. 159, and Vol. 31, p. 165. A mixture of four brands of normal cements and two different high-early-strength cements were used. Aggregates were Elgin sand and gravel passing a $\frac{3}{4}$-in. sieve. Workable mixes of 2 to 6-in. slump containing $4\frac{1}{2}$, 6, and 9 gal. of water per sack of cement were made with each cement. Four 3 by 6-in. cylinders cast and puddled in standard manner were made in paraffin-treated cardboard molds for each test condition. Prior to low temperature exposures, specimens were given a preliminary curing in the uncovered molds for the periods indicated in subsequent diagrams. Specimens were removed from cold storage when 1, 3, 7, or 28 days old. Subsequent to cold temperature exposure, certain specimens were stripped of their molds and cured at warm temperatures in air at 50 per cent humidity for various periods. Molds and materials were brought to the casting temperature indicated before the specimens were molded. All specimens were soaked 1 to 3 hr. in water at 70° F., immediately before testing.

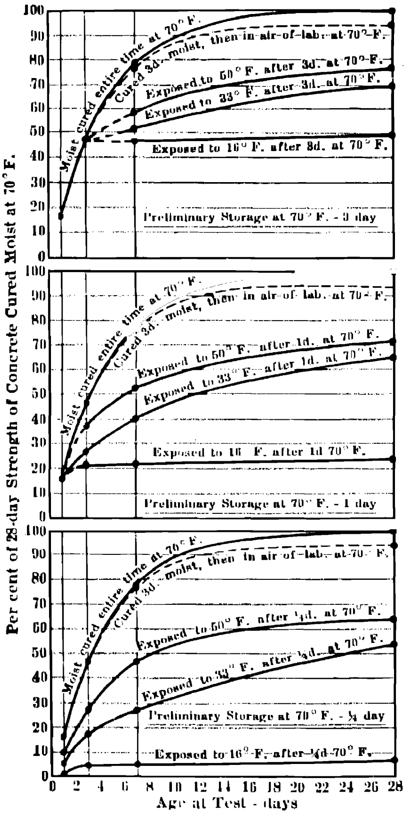

FIG. 23.—Relative Strength of Concrete as Influenced by Storage Temperature. w/c = 0.8, by vol., slump 3 to 5 in.

Figures 23 and 24, taken from the Timms and Withey report, show relations useful in design. In Fig. 23 is shown the relative strength of concrete with a water content of 6 gal. per sack placed at 70° F. for $\frac{1}{4}$, 1, or 3 days and then treated as indicated. Specimens exposed at 16°, 33°, and 50° F. were in uncovered cardboard molds in a cold room. The concrete represented was of excellent quality. Its w/c, by wt., was 0.53, and its compressive strength moist-cured at 70° F. for 28 days was about 5200 lb./in.^{2}. This figure shows the marked retardation in hardening suffered by concrete when placed at low temperatures.

Further data given in the report show that practically the full potential strength of a concrete subjected to such low temperatures can be developed provided it is *kept saturated* during the warming period, but warming in an atmosphere at 50 per cent relative humidity was not a satisfactory procedure.

Figure 24 is an aid in designing concrete placed in cold weather but subjected to 50° F. curing temperature. In the upper four diagrams the design strength, given by the upper dash lines, is *based* on concrete cured in molds 1 day then moist at 70° F., whereas in the lower four diagrams the design strength is *based* on water curing at 72° F. after removal of molds. The solid lines represent the relative strengths of concrete given the preliminary storage at normal temperatures, then in air, or water, at 50° F. The dotted lines indicate strengths for concrete after preliminary storage of 1 day in air at 50° F., followed by storage in air or water at 50° F.

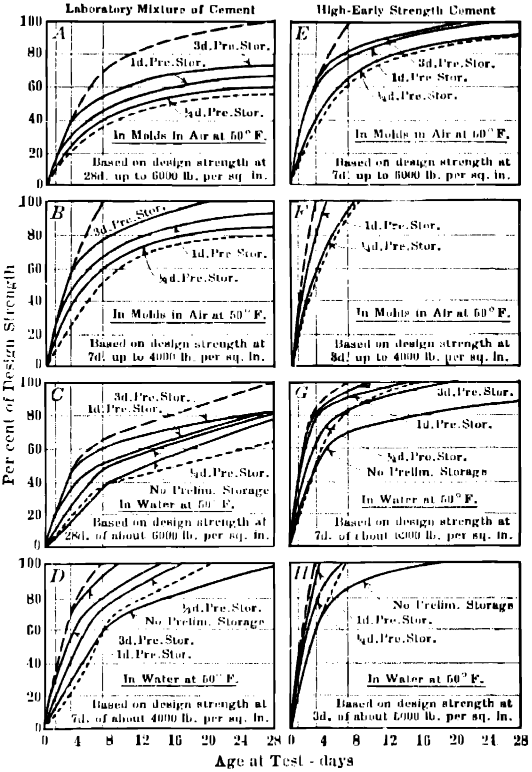

FIG. 24.—Relative Compressive Strength of Concrete Stored at 50° F. Based on Wet Curing at 70° F.

As an example of the use of Fig. 24 assume that the relative 7- and

28-day strengths of concrete made of normal cement and subjected to curing at 50° F. in air are wanted in terms of the 7-day normal strength. From the dotted curve in diagram *B* the respective ratios are 0.5 and 0.8. Hence the estimated 28-day strength of concrete cured in air at 50° F. is 80 per cent of the 7-day strength normally cured.

In *Proc. A.S.T.M.*, Vol. 37, p. 306, H. H. Scofield reports freezing tests made at Cornell University on 1500 specimens. These tests show the effect of immediate and delayed freezing on the strength, stiffness, and permeability of concretes and mortars made from 6 types of cement. His data on the effect of immediate freezing are given in Table 13. Cement No. 1 was normal Portland; No. 2, a high-early-strength Portland; No. 3, a waterproofed Portland; and No. 4, a high-alumina cement. Specimens frozen immediately were placed in the cold room at 10° F. as soon as molded. The temperature within the 6 by 12-in. cylinders reached 32° F. in 3 to 4 hr. and 10° F. in about 12 hr. All specimens were moist-cured after the freezing period. Each result represents at least 3 tests. These

TABLE 13.—EFFECT OF IMMEDIATE FREEZING ON THE STRENGTH OF CONCRETE. (SCOFIELD)

Actual compressive strength in pounds per square inch is given for all normal (0-days frozen) results.
Ages given are for moist curing periods after frozen period.

Cement	Slump, in.	Frozen Period, days	Compressive Strength of Previously Frozen Concrete as Percentage of the Strength of the Normal Concrete at the Same Age									
			1 : 2 : 3 Concrete					1 : 3 : 5 Concrete				
			7 days	28 days	1 yr.	4 yr.	Average, per cent	7 days	28 days	1 yr.	4 yr.	Average, per cent
No. 1	2	0	2387	4180	6773	6787	100	1502	2777	4045	4665	100
		1	61.6	55.1	64.4	67.8	62.2	40.2	43.2	55.5	55.4	48.6
		7	57.6	51.0	55.6	64.3	57.1	38.5	37.4	53.4	51.7	45.2
No. 2	2	0	4000	4996	6370	7040	100	3075	3690	4815	4596	100
		1	50.0	61.7	57.0	58.4	54.8	54.0	67.7	63.1	71.8	60.6
		7	44.2	56.7	60.5	53.8	53.8	42.3	56.9	59.4	58.7	54.3
No. 3	2	0	1750	3055	4335	4567	100	1090	1990	3760	3061	100
		1	44.6	48.5	73.4	77.2	60.9	51.4	50.2	70.3	76.0	62.3
		7	52.0	51.7	72.2	65.7	60.4	50.4	49.2	60.0	77.7	58.7
No. 1	6	0	2300	3677	6046	5685	100	1118	2033	3433	4063	100
		1	48.8	51.2	55.1	67.7	55.7	37.2	37.0	44.4	50.6	42.8
		7	47.5	50.1	54.7	63.1	53.8	33.7	37.2	43.7	45.1	39.9
No. 2	6	0	3605	4630	5572	5692	100	2390	3290	3990	3656	100
		1	38.4	46.0	51.3	55.2	47.7	50.6	57.1	50.9	57.1	53.9
		7	36.9	43.5	52.8	56.3	47.4	43.0	43.4	50.0	61.0	49.3
No. 3	6	0	1750	3160	4725	5291	100	990	1770	3250	3005	100
		1	45.7	57.0	70.9	65.3	58.7	51.1	57.7	52.9	59.0	55.4
		7	46.8	49.7	55.7	60.0	53.5	48.0	50.9	50.6	57.9	51.8
No. 4	6	0	4970	4022	5755	5872	100	2775	2780	3538	2788	100
		1	87.7	97.7	88.5	101.0	93.7	69.0	70.0	65.4	68.5	68.2
		7	85.0	97.0	97.4	92.7	93.0	70.3	77.3	81.0	72.7	75.3
No. 1	9	0	1840	3047	5123	4738	100	825	1453	2640	2950	100
		1	53.0	54.7	60.5	71.1	60.6	49.0	49.3	52.1	62.6	53.2
		7	38.7	52.0	51.3	64.7	51.7	39.7	46.0	46.8	54.4	46.7

data show that concrete of Portland or high-early-strength Portland cement loses from 40 to 60 per cent of its potential strength and stiffness when frozen immediately. Varying the length of the freezing period had little effect. The drier mixes of 2-in. slump suffered somewhat less than the wet mixes, especially at the early ages. The influence of freezing in increasing permeability was marked, especially at the early ages and for specimens frozen 7 days. Here again the leaner mix was most affected. The high-alumina-cement concrete developed much higher percentages of its potential strength and stiffness and exhibited no leakage after freezing.

Scofield's data on effect of delayed freezing showed that the full potential strength of the 2-in. slump mixes could subsequently be developed by moist-curing, provided the concrete was given 24 to 48 hr. in room-dry conditions prior to freezing. For the wet mixes of 9-in. slump, 3 or 4 days of such preliminary curing were required before freezing in order to avoid injury. His data indicated that moist-cured specimens required longer precuring than air-cured specimens in order to avoid permanent injury by freezing.

Several alternate freezings and thawings prior to hardening are more injurious than continuous freezing. A few tests by W. C. F. Rath in a thesis in 1906 at the University of Wisconsin indicate that the greatest injury was done to the cements then used when the intervening thawing periods were 4 to 6 days apart.

540. The Rate of Cooling of Concrete Setting at Low Temperatures.— A number of tests on rapidly cooled concrete wallettes were made by O. A. Bailey and F. D. Bickel at the University of Wisconsin in 1915. The wallettes were 30 by 24 by 6 or 12 in. They were cast in 1½-in. pine forms in a refrigerator at temperatures about 10° F. The wallettes were cast with a dividing partition of galvanized iron so that 12 by 12 by 24-in. prisms could be removed and tested. Data on 1 : 2 : 4 gravel concrete of medium consistency made with several Portland cements indicated that such concrete placed in 2-in. plank forms with top covered will set before it freezes, provided the temperature of the concrete at pouring is 100° F., the wall 6 in. or more thick, and the outside temperature 0° F., or above.

Methods of calculating temperature changes in setting and hardening concrete, and of evaluating the accompanying stresses, are discussed by R. W. Carlson in *Proc. Am. Conc. Inst.*, Vol. 34, p. 89 and p. 497.

541. Alternate Freezing and Thawing Tests on Hardened Concrete.— Although thus far no fixed procedure has been adopted for measuring the resistance of masonry materials to freezing and thawing, progress has been made (see Rept. of Committee on Cements, *Proc. Highway Research Board*, 1936; also *Rept. of Building Research Board*, 1927 and 1928).

Among the influential factors are (1) the criterion to use in judging the effects of the test, (2) method of immersion of specimen, (3) rate of lowering temperature through the freezing point, (4) method and rate of thawing, (5) number of cycles required as a criterion. The following procedure has been used successfully at the University of Wisconsin.

Make and cure in accordance with standard methods 3 to 5 prisms for each condition to be tested. These can be tested as beams, then broken as modified cubes in compression, and, if desired, used for expansion and loss in weight measurements prior to testing for strength. For concrete 6 by 6 by 18-in. and for mortars 2 by 2 by 9-in. prisms are satisfactory specimens. Soak specimens 24 hr. prior to freezing and support with top surface as molded down in trays of water 1 in. deep. The trays should be cooled at such rate that the recorded temperature at the center of a prism will drop from 32° F. to 15° F. in not less than 3 hr. and not more than 5 hr. After freezing, thaw one hour in water at 70° F. Repeat for 100 cycles; make determinations of differences in strength, weight, etc., between the normally cured and the frozen and thawed specimens. Standardize condition of specimens by soaking in water prior to making such determinations.

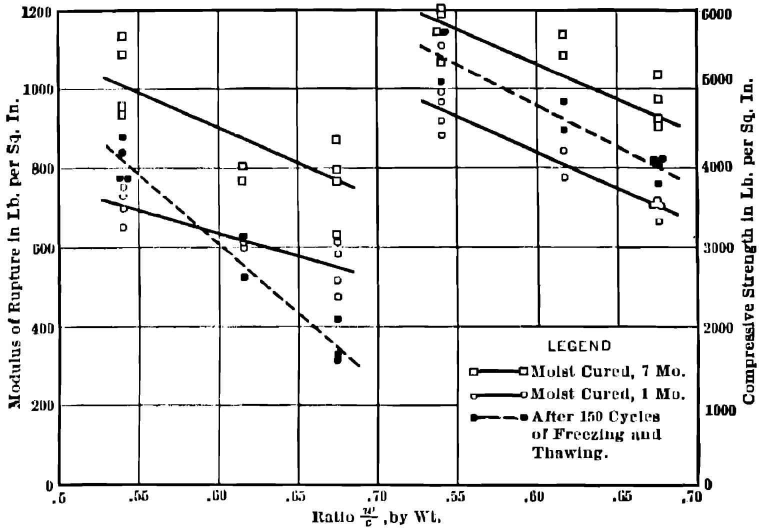

FIG. 25.—Effect of Freezing and Thawing on the Strength of Concrete Made of Crushed Dolomite. (*Proc. Am. Conc. Inst.*, Vol. 35, p. 553.)

Figure 25 shows the effects of 150 cycles of freezing and thawing on 6 by 6 by 18-in. prisms of excellent vibrated concrete tested as suggested. Concretes with water-cement ratios above 0.54 exhibited marked reductions in modulus of rupture due to freezing and thawing.

After 100 cycles of such test, durable concrete should have a modulus of rupture not less than 80 per cent of that of similar concrete of the same age.

TABLE 14.—THE EFFECT OF CALCIUM CHLORIDE AND SODIUM CHLORIDE ON THE COMPRESSIVE STRENGTH OF 1 : 2 : 4 CONCRETE

Materials:—Atlas cement, good pit sand weighing 108 lb. per cu.ft., and limestone passing a 1½-in. mesh and weighing 90 lb. per cu.ft.

Consistency:—Wet.

Storage:—Normal specimens stored in air one day, in water 13 days. Low-temperature specimens, placed out of doors or in a refrigerator immediately after molding, remaining frozen until tested.

Testing:—Each result represents tests on 4-in. cubes. Specimens were embedded in blotting paper on a spherical bearing block.

Per Cent Salt.		Specimens Cured at Room Temp.				Specimens Cured at Low Temp.			
$CaCl_2$	NaCl.	Temp. of Batch at Mixing, °F.	Compressive Strength in Lb. per Sq.In. at			Temp. (in °F.) at Mixing.		Compressive Strength in Lb. per Sq.In. at	
			14 Days.	60 Days.	360 Days.	Batch.	Out of Doors.	14 Days.	60 Days
0	0	52	1910	3010	3580	52	13	213	427
0	6	52	1684	2620	2895	51	13	482	685
0	9	65	1525	2385	3055	51	13	680	942
0	12	68	1270	2060	2485	51	13	813	1192
0	15	58	1335	2220	2740	42	13	614	1060
2	0	59	1920	3220	3740	41	17	420	466
4	0	60	2105	3510	3880	44	17	444	564
6	0	60	1725	3280	3670	55	18	349*	367*
8	0	61	1510	3070	3155	46	1	286*	334*
10	0	61	1655	3025	3330	46	1	234*	348*
2	6	59	1600	2650	3150	52	15	817	992
2	9	63	1695	2590	3100	52	15	848	1185
2	12	64	1420	2440	2805	41	7	690	1045
2	15	60	1320	2350	2725	38	7	583	801
4	6	56	1685	2550	2960	52	21	785	914
4	9	58	1550	2390	2965	51	20	755	926
4	12	58	1710	2935	3680	45	15	766	1215
4	15	55	1245	1880	2410	45	15	713	1200
6	6	60	1310	2475	2575	43	20	680	988
6	9	54	1305	2370	3025	38	20	480	850
6	12	54	1345	2420	......	52	21	505	615
6	15	52	1380	2415	......	52	21	527	863
8	6	60	1120	2075	2490	51	21	390	580†
8	9	58	1135	2085	2445	50	30	487	654
8	12	60	1110	1995	2525	52	30	402	589
8	15	59	1550	2605	2940	44	14	535	658†

* Badly disintegrated.

† Edges were spalled to some extent.

542. The Effect of Adulterants in Lowering the Freezing Point.—Small percentages of salt or calcium chloride dissolved in the mixing water serve to lower the freezing point of the mix and thereby permit hardening at temperatures lower than 32° F. With some cements the use of small percentages of salt appears to diminish the strength; with others the reverse is true. So far as published results show, the use of a 10 or 12 per cent (by weight) solution of common salt has rarely decreased the long-time strength over 25 or 30 per cent, and in most cases the weakening in final strength is much less. The use of salt in reinforced concrete should be prohibited, since in damp locations it may cause rusting of the steel. A common rule for the use of salt is: Add 1 per cent of salt to the mixing water for each degree Fahrenheit below 32.

Tests by H. E. Pulver and S. E. Johnson * at the University of Wisconsin, on the effects of calcium and sodium chloride solutions on the strength of 1 : 2 : 4 concrete subjected to freezing conditions, are abstracted in Table 14. The combination of 2 per cent calcium chloride with 9 per cent sodium chloride gave the best results of any of the salt solutions under freezing temperatures. Since calcium chloride alone greatly hastens the set, its employment in the field will require very rapid handling during pouring.

543. Resistance of Concrete and Mortar to High Temperatures.—Observations after conflagrations like the San Francisco, Baltimore, and Chelsea fires have shown that concrete possesses a high resistance to fire. Many examples have been cited of concrete buildings which were left standing alone in fire-swept areas of these cities.

A series of 215 tests on concrete-block walls 5½ by 6 ft. and of 4, 8, and 12 in. thickness were made at the Portland Cement Assoc. Laboratory and reported by C. A. Menzel in *Proc. A.S.T.M.*, Vol. 31, Pt. 1, p. 607, and *Proc. Am. Conc. Inst.*, Vol. 29, p. 113. Excepting the size of wall, the fire tests on 165 of the walls were made in accordance with the requirements of *Tent. American Standard* A2-1926. The program included 9 types of aggregate and variables in grading, cement content, type of block, mortar, workmanship, and use of plaster.

Machine-tamped units were moist-cured 5 days, then aged 2 weeks in laboratory until laid. In most of the tests a 1 Portland cement : 0.15 hydrated lime : 3 sand mix, by dry rodded volume, was used. The walls were tested at ages of 45 to 60 days. Walls were first loaded to 240 lb./in.^{2} of gross area and measurements of deformations and deflections taken. During the fire test the walls were exposed on one face and loaded with 80 lb./in.^{2} on gross area. In most tests the fire exposure extended for 1¼ hr. for 4-in. walls, 3 to 3½ hr. for 8-in., and 5 to 6½ hr. for 12-in. walls. Measurements were made of both furnace and block temperatures by 33 thermocouples and 9 thermometers. The average temperatures of the furnace after ½, 1, 3 hr., and 6 hr. approximated 1540, 1700, 1920, and 2140° F.

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* *Concrete Cement Age*, Vol. 3, p. 256.

Since only one wall failed under load during the fire test, the evaluation of performance was based on the time required for the average temperature on the unexposed face to exceed by 250° F. its initial temperature, or the maximum at any point to exceed the initial value by 325° F. After the fire exposure, the walls cooled under the load of 80 lb./in.^{2} for 24 hr. and were then progressively loaded to failure.

In one series of Menzel's tests the cement content was held at 4.3 lb. per block, and the grading of the aggregate was changed so that values of the fineness modulus (m) ranged from 2.0 to 4.75. Results showed a marked increase in strength of both units and walls after fire as m was raised up to the values shown in Table 15. On the other hand the fire-endurance period was about 15 per cent longer for the blocks containing the most fine material. The data in Table 15 show that there is an increase in endurance period, strength of unit, and wall after exposure with increase

TABLE 15.—FIRE ENDURANCE AND STRENGTH OF WALLS OF DIFFERENT CEMENT CONTENTS. (MENZEL)

Walls 8 in. thick made with 3-oval-core blocks.
Descriptions of aggregates used are given in notes accompanying Table 16.

Fineness Modulus	Mix by Volume	Cement Content		Average Weight of Air-Dry Block, lb.	Fire Endurance Period, minutes	Ultimate Strength, lb. per sq. in. Gross Area		Ratio of Wall Strength to Original Strength of Unit, per cent
		Block per Sack	Lb. per Block			Block Before Fire Exposure	Wall After Fire Exposure Indicated	
CALCAREOUS SAND AND GRAVEL AGGREGATES								
4.50	1 : 14.0	40.0	2.35	46.4	133	920	270 (3 hr.)	29
4.50	1 : 11.0	30.0	3.13	48.5	135	1160	310 (3 hr.)	27
4.50	1 : 7.0	19.0	4.95	51.1	142	2440	560 (3 hr.)	23
4.50	1 : 5.0	14.3	6.58	51.6	149	2300	550 (3 hr.)	24
4.50	1 : 4.0	11.1	8.45	52.4	154	3350	615 (3 hr.)	18
4.50	1 : 3.0	9.3	10.10	52.4	162	3550	750 (3 hr.)	21
SILICEOUS SAND AND GRAVEL AGGREGATE "A"								
4.25	1 : 14.0	38.5	2.44	44.5	[a]	725	[a]	[a]
4.25	1 : 7.5	21.2	4.42	46.4	118	1810	480 (3 hr.)	26
4.25	1 : 3.0	9.3	10.10	49.6	137	4075	855 (3 hr.)	21
HAYDITE AGGREGATE								
3.25	1 : 10.0	29.1	3.23	26.8	160	750	256 (3½ hr.)	34
3.25	1 : 8.0	23.6	3.98	27.8	174	1000	445 (3½ hr.)	44
3.25	1 : 7.0	21.1	4.45	28.2	178	1120	358 (3½ hr.)	32
3.25	1 : 5.0	15.3	6.15	30.0	194	1575	580 (3½ hr.)	37
3.25	1 : 3.0	9.8	9.60	32.8	221	2100	770 (4 hr.)	37

[a] This wall failed at 93 minutes of fire exposure under the working load of 80 lb. per sq. in. of gross area and was withdrawn from the furnace at 94 minutes. Readings of temperatures on the unexposed surface which were continued indicated that an average rise of 250° F. was attained at 114 minutes and the maximum rise of 325° F. at 122 minutes. Had the exposure to fire been continued for about 20 minutes longer, it is estimated that the average temperature rise of 250° F. would have been attained about 5 minutes earlier or at 109 minutes.

in cement content, although it does not appear that more than 4.5 to 5 lb. of cement per block of the type tested would be effectively used. Table 16 presents data showing the relative endurance of walls made of various aggregates. The fire endurance expressed in minutes per pound per square foot of wall surface shows the advantages of the lighter-weight materials based on fire resistance. On the other hand, as evidenced by data in Table 15, in order to produce a given wall strength a higher cement content must be used with the lighter-weight aggregates.

The increased strength obtained by bedding both face shells and transverse webs in mortar as compared to bedding face shells alone is well

TABLE 16.—INFLUENCE OF AGGREGATE ON FIRE RESISTANCE OF WALLS.

(MENZEL)

Walls 8 in. thick made with 3-oval-core block.

Description of aggregates:

Siliceous Sand and Gravel (B): A highly siliceous aggregate (85 per cent silica in form of quartz) containing very little calcareous material. Particles range from regular to irregular in shape but generally with well-rounded edges and hard smooth surfaces.

Siliceous Sand and Gravel (A): A somewhat more siliceous aggregate than aggregate (B) (95 per cent silica in form of flint and chert). Particles very irregular with both sharp and slightly rounded edges and both polished and pitted surfaces.

Calcareous Sand and Gravel: A typical calcareous aggregate containing about 40 per cent calcium carbonate, 30 per cent magnesium carbonate, and less than 15 per cent quartz. Particles range from regular to irregular in shape but generally with well-rounded edges. Surfaces varied from smooth, slippery texture to a rough porous pitted type with neither type predominating.

Crushed Limestone: Typical of crushed calcareous stone of dolomitic variety containing roughly 50 per cent of calcium carbonate, 30 per cent magnesium carbonate, and with less than 5 per cent quartz. Particles very irregular in shape with slightly rounded sharp edges. Surfaces were somewhat slippery to the touch and slightly porous.

Crushed Common Brick: Typical of the fine and coarse low fusing porous burned clay aggregate produced by crushing common brick. Particles very irregular in shape with sharp rough edges and rough pitted surfaces.

Crushed Fire Brick: Typical of the fine and coarse highly refractory porous burned clay aggregate produced by crushing broken pieces of fire brick and other shapes of similar refractory material. Particles very irregular in shape with very rough edges and deeply pitted exceedingly rough surfaces.

Haydite: A light, porous, aggregate material prepared by burning shale to incipient fusion and crushing and grading the resulting clinker. Particles irregular in shape with slightly rounded sharp edges and slightly rough porous and pitted surfaces. Unless otherwise noted the Haydite aggregate used in this and other groups of tests came from the same source.

Air-Cooled Blast Furnace Slag: Typical of the slag discharged from blast furnace and brought from the molten to solid form by cooling in air.

Soft Coal Cinders: Typical of the porous clinkerous ash resulting from the high temperature combustion of soft coal in the modern power plant. It contained about 12 per cent of combustible material principally in the form of coke and to a minor extent as soft coal. Particles irregular in shape with both sharp and well-rounded edges and both glossy and rough pitted porous surfaces.

Coke Breeze: This material consists of screenings ranging from dust to ⅜ in. of the highly porous product commonly used as fuel known as coke. It consists almost entirely of carbon (ash 12 to 14 per cent) and is the product remaining after the hydrocarbon gases have been distilled from soft coal in the manufacture of gas. Particles irregular in shape with slightly rounded sharp edges and rough deeply pitted exceedingly porous surfaces.

Aggregate			Mix by Volume	Cement Content		Average Air-Dry Weight, lb.		Fire Endurance Period, minutes	
Type	Fineness Modulus	Unit Weight, lb. per cu. ft.[a]		Blocks per Sack	Lb. per Block	Per Block	Per sq. ft. of Wall	Wall	Per lb. per sq. ft. of Wall
Coke Breeze	3.50	49	1 : 7.5	21.2	4.44	23.5	29.0	110	3.79
Siliceous Gravel A	3.50	115	1 : 7.5	21.8	4.30	45.2	53.2	124	2.33
Siliceous Gravel B	3.70	113	1 : 8.3	22.5	4.18	46.7	54.9	129	2.35
Crushed Fire Brick	3.50	91	1 : 7.5	21.9	4.29	36.8	43.8	145	3.21
Calcareous Gravel	3.50	120	1 : 7.8	22.4	4.20	46.6	54.8	150	2.74
Crushed Limestone	3.50	120	1 : 7.8	21.7	4.33	49.0	57.4	158	2.75
Soft Coal Cinders	3.25	79	1 : 7.0	20.6	4.56	33.9	40.6	163	4.01
Haydite	3.50	67	1 : 7.0	21.2	4.43	27.6	33.5	168	5.01
Crushed Common Brick	3.50	77	1 : 7.5	21.6	4.36	32.3	38.8	175	4.51
Air-Cooled Slag	3.50	102	1 : 7.5	22.0	4.25	41.1	48.7	193	3.96

[a] Based on dry rodded 0 to ⅜-in. aggregate graded to fineness modulus indicated.

shown in Table 17 from Menzel's tests. His tests showed that a half inch of gypsum plaster applied to either face of an 8-in. block wall increased the fire-endurance period 30 per cent. If applied to both faces, the increase was 60 per cent. Plaster also increased appreciably the wall strength after fire exposure. Tests of units of various designs indicated that the length of the fire-endurance period was closely related to the weight per square foot of wall surface. An increase of 50 per cent in that weight doubled the fire-endurance period. There was little effect on wall strength after exposure to fire, owing to the presence of coke and coal in soft coal cinders up to 33 per cent by weight of the cinders. Filling the cells of the units with sand, Haydite, or granulated slag increased the fire-endurance period $2\frac{1}{2}$ times.

TABLE 17.—STRENGTH OF WALLS LAID UP WITH DIFFERENT TYPES OF MORTAR JOINTS

Block units made from aggregate graded from 0 to $\frac{3}{8}$ in. and from mixes ranging from 1 : 5 to 1 : 14 by volume of cement to dry rodded volume of aggregate. Walls laid up with 1 : 3 Portland cement mortar plus 15 per cent hydrated lime by volume of cement.

Type of Mortar Bed Construction	Application of Mortar at Horizontal Joints	Type of Aggregate	Ratio of Wall Strength after Fire Exposure Indicated to Original Strength of Unit, Per Cent		Improvement in Wall Strength with Full Mortar Bedding over Face Shell Bedding, Per Cent	
			Before Fire	After Fire	Before Fire	After Fire
Face Shell Bedding	Face Shells Only	Haydite	55	36 ($3\frac{1}{2}$ hr.)	. .	. .
		Calcareous	55	28 (3 hr.)	. .	. .
		Siliceous	55	22 (3 hr.)	. .	. .
Full Bedding	Face Shells and Transverse Webs	Haydite	70	49 ($3\frac{1}{2}$ hr.)	27	36
		Calcareous	70	43 (3 hr.)	27	53
		Siliceous	70	36 (3 hr.)	27	64

Menzel's tests demonstrate that the expansion in the 6-ft. height of walls averaged $\frac{1}{6}$ to $\frac{1}{8}$ in. for walls made with cinders, blast furnace, slag, coke breeze, brick, and Haydite; $\frac{3}{16}$ to $\frac{3}{8}$ in. for walls with limestone, calcareous sand, and gravel; and $\frac{5}{16}$ to $\frac{9}{16}$ in. for walls with highly siliceous sand and gravel. They all bowed towards the fire and were thus eccentrically loaded during the test to destruction. The moduli of elasticity for the walls prior to test ranged from 200,000 to 750,000 lb./in.^{2}; after exposure, from 100,000 to 300,000 lb./in.^{2} on gross area. For 8-in. walls the modulus after exposure was about 40 per cent of the initial value. The high strengths of these walls after the fire test are heartening evidence of the resistance of this type of construction to fire. The linear relation of the strength of walls after exposure to strength of unit is also a most important contribution.

In the foregoing tests it should be noted that only the exposed face shell of the units became heated to 1000° F. Tests by I. H. Woolson (*Proc. A.S.T.M.*, Vol. 5, p. 335, and Vol. 7, p. 404) on 4-in. cubes of

TABLE 18.—LINEAR COEFFICIENT OF EXPANSION OF CONCRETE AND MORTAR AT NORMAL TEMPERATURES

Mix.	Aggregate.	Coefficient per °F.	Authority.	Reference.
1 : 0	. . . .	.0000070	Keller	*Tonind'z'l'g*, No. 24, 1904
1 : 2	Pit gravel	.0000056	Keller	
1 : 4	Pit gravel	.0000058	Keller	
1 : 8	Pit gravel	.0000053	Keller	
1 : 2 : 4	Sand and limestone	.0000055	Pence	*Jour. W. S. E.*, Vol. 6, p. 549
1 : 2 : 4	Sand and gravel	.0000054	Pence	
1 : 4½	Quartz	.0000066	Davis and Troxell	*Proc. Am. Conc. Inst.*, Vol. 26, p. 438
1 : 4½	Sandstone	.0000065		
1 : 4½	Gravel	.0000060		
1 : 4½	Granite	.0000053		
1 : 4½	Basalt	.0000048		
1 : 4½	Limestone	.0000038		

TABLE 19.—THE SPECIFIC HEAT OF CONCRETE. (NORTON)

Range of Temp. ° F.	1 : 2 : 5 Stone Concrete.	1 : 2 : 4 Stone Concrete.	1 : 2 : 4 Cinder Concrete.
72 to 212	0.156	0.154	
72 to 372	0.192	0.190	0.180
72 to 1172	0.201	0.210	0.206
72 to 1472	0.219	0.214	0.218

TABLE 20.—THE COEFFICIENT OF THERMAL CONDUCTIVITY OF CONCRETE. (NORTON)

Temperature of Hot Side of Plate in Degrees.		Mixture.	Coefficient in Calories per 1 Deg. C. per Sq.Cm. per Cm. per Sec.	Coefficient In B.T.U. per 1 Deg. F. per Sq. Ft. per In. Thick per 24 Hr.
C.	F.			
35	95	Stone 1 : 2 : 5	0.00216	150
50	122	Stone 1 : 2 : 4 not tamped	0.00110 to 0.00160	76 to 114
50	122	Cinder 1 : 2 : 4	0.00081	56
200	392	Stone 1 : 2 : 4	0.0021	146
400	752	Stone 1 : 2 : 4	0.0022	153
500	932	Stone 1 : 2 : 4	0.0023	160
1000	1832	Stone 1 : 2 : 4	0.0027	188
1100	2012	Stone 1 : 2 : 4	0.0029	202

1 : 2 : 4 concrete showed that limestone concrete heated throughout to a temperature of 1250° F. lost half its strength and that trap rock concrete was so injured at a temperature of 1700° F. Woolson's tests showed that the modulus of elasticity of concrete of either trap rock or limestone was reduced 60 per cent by heating to 500° F. At 1500° F. the modulus was only a tenth of the normal value.

544. The Coefficient of Expansion of Concrete and Mortar.—Table 18 contains values of the linear coefficient of thermal expansion of concrete for atmospheric ranges of temperature. The coefficient for concrete approximates the weighted mean of the coefficients of the neat cement and aggregates. An average for common mixes is 0.0000055 per °F.

545. Other Thermal Properties.—Tests by C. L. Norton * on the specific heat of various mixtures of concrete gave the results in Table 19. In these tests he employed Regnault's method of mixtures, using an ordinary double calorimeter.

Norton also determined the coefficient of thermal conductivity (K) for concrete.

$$K = \frac{Qd}{(t_1 - t_2)As}$$

in which Q = the quantity of heat flowing through a plate whose area $= A$ and thickness $= d$, s is the time of flow, and t_1 and t_2 the temperatures on the hotter and cooler sides of the plate, respectively. His results for various types of concrete appear in Table 20. It will be noted that the conductivity of cinder concrete is only about 40 per cent that of stone concrete.

Although concrete is superior to the metals and natural stones, it must not be considered a first-class insulating material. At room temperatures it is greatly surpassed as a heat insulator by asbestos, mill shavings, powdered magnesia, mineral wool, hair felt, pulverized cork, and hair cloth; and at high temperatures it is inferior to such substances as asbestos, infusorial earth, and powdered magnesia. The protective value of concrete lies in a high resistance to fire coupled with a fairly low conductivity and high strength.

Woolson also determined the rate of flow of heat into different classes of concrete when the exposed face of the block was subjected to a temperature of 1500° F. His measurements were made by Le Châtelier pyrometers placed at distances of ½, 2, 3, 4, 5, 6, and 7 in. from the exposed faces of rectangular prisms 8 in. deep and 7¼ × 13½ in. in elevation. After one hour at the above temperature the records obtained on single specimens of 1 : 2 : 5 cinder, 1 : 2 : 4 gravel, and 1 : 2 : 4 trap rock concrete are shown in Fig. 26.

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* *Proc. Nat. Asso. Cement Users*, Vol. 7, p. 78.

In certain tests Woolson embedded $\frac{3}{4}$-in. bars in the axes of 8×8×36-in. concrete blocks. These blocks were of similar proportions and ingredients to those mentioned above. The bars were cut longer than the blocks and

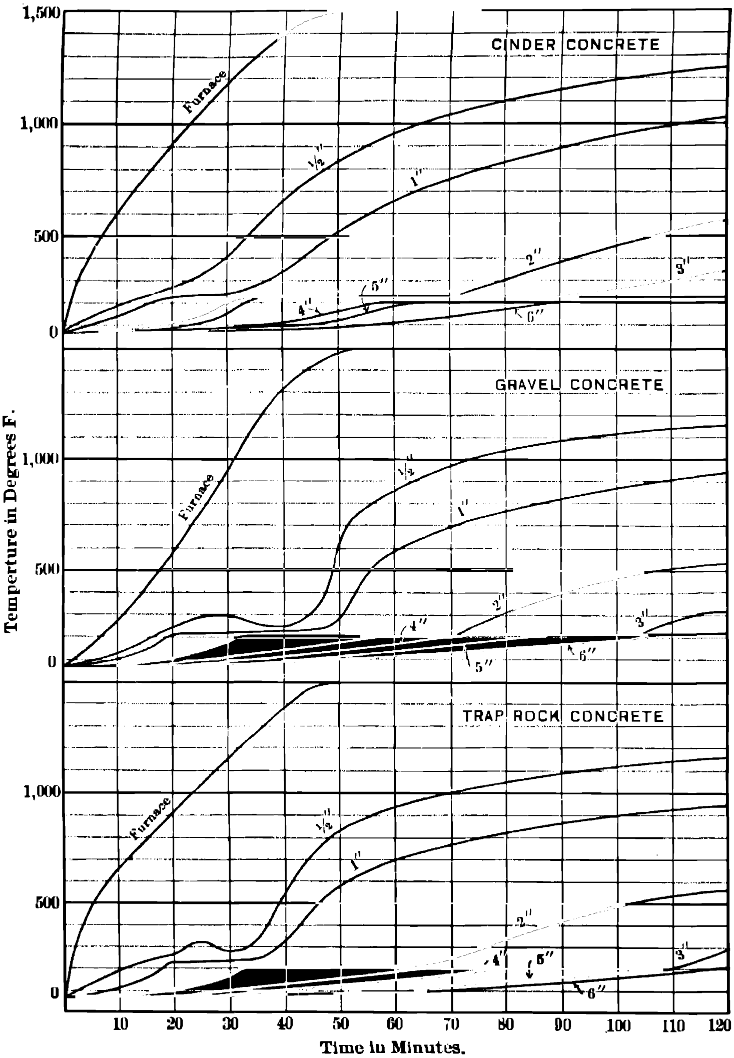

FIG. 26.—The Thermal Conductivity of Concrete. (Woolson, *Proc. A.S.T.M.*, Vol. 7, p. 406.)

projected from either 8 × 8-in. face. One 8 × 8-in. face was gradually heated to 1700° F. and measurements of the temperature at different points along the bar were made. After one hour at the above temperature a point on a bar 2 in. from the exposed face of the prism had a temperature of only 700° to 1000° F.; a point 5 in. from the surface reached 400° F. to 500° F.; while a point 8 in. from the surface attained the temperature of boiling water. These tests and others indicate that 2 in. of good concrete affords ample protection to embedded steel against fire.

In the previously mentioned tests conducted by Humphrey, the maximum temperature at the outside surface of the 8-in. walls, made of concrete beams, varied from 58° C. for the granite to 43° C. for the cinder concrete. This was obtained after the inside temperature had been held at 800–1000° C. for about one and one-half hours.*

A few experiments † on hollow concrete cylinders 36 in. inside diameter, 36 in. high and 6 to 8 in. thick, showed that the temperature gradient through the walls approximated a straight line after the internal temperature had been maintained constant at 700° F. and the outside at room temperature for a couple of days. A 1 : 2 : 4 concrete made of limestone was used.

THE DURABILITY OF CONCRETE

546. Effect of Sea Water.—Although no masonry material has been developed which is permanent when subjected to sea water in our northern latitudes, concrete can be made relatively durable under such exposure. The relative resistances of various types of cement to the attack of sea water have been considered in Art. 362. In marine concrete, durable materials must be used and dense smooth hard surfaces secured. Segregation and laitance should be avoided by using properly graded aggregates and by prohibiting sloppy or non-placeable mixtures. For exposed surfaces, a water cement-ratio not more than 0.8, by vol., is suggested.

In 1896 the Society of Scandinavian Portland Cement Manufacturers subjected 3500 2.8-in. mortar cubes and over 100 blocks of concrete, each a cubic yard in volume, to the action of the sea. Proportions of mortars were neat, 1 : 1, 1 : 2, and 1 : 3, of concrete 1 : 1 : $2\frac{7}{8}$, 1 : 2 : 4, and 1 : 3 : $5\frac{1}{8}$. Specimens were cured in fresh water and then immersed in 5 different localities where the severity of action and concentration of salt varied widely. Some specimens were always submerged; others at mid-tide only. From Poulsen's report after 10 years (*Proc. I.A.T.M.*, 5th Congress, XI_4, the following conclusions are drawn:

1. Chemical action of sea water alone does not cause destruction of Portland cement mortars and concretes.

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* For the calculation of the rate of flow of heat into concrete and other materials reference may be made to Ingersoll and Zoebel's *The Mathematical Theory of Heat Conduction, with Engineering and Geological Applications;* also *Engr. News,* Vol. 70, p. 866.

† Thesis by Melin and Pulver, University of Wisconsin, 1910.

2. Climatic conditions, principally the mechanical action of the tides and frost, are chiefly responsible for the disintegration of concrete and mortar mixtures in sea water. The hydraulic lime from Teil was especially adversely affected by the midtide treatment at Vardo.

3. Mixtures containing mortars leaner than 1 : 2 should not be used in maritime construction.

4. From the tests on graded mixtures, sands for marine concrete should contain from $\frac{1}{3}$ to $\frac{2}{3}$ of particles passing a No. 30 sieve.

A valuable set of experiments on the effect of sea water on concrete was begun in 1909 by the Aberthaw Construction Company of Boston. Twenty-four piers 16 ft. × 16 in. × 16 in. are suspended from a wharf in Boston harbor so that both the effect of continued submergence below low water and the action of the tides can be observed. Crushed trap rock, 98.25 per cent of which was between $1\frac{1}{2}$ and $\frac{1}{4}$ in. diameter, and a good bank sand, 52 per cent of which passed a No. 30 sieve, were the aggregates. Portland cements of high, medium, and low alumina contents, iron ore cement, and slag Portland cement were used. One pier of 1 : 3 : 6 proportions was made with 10 per cent of the cement replaced by hydrated lime, another with 5 per cent of pulverized clay, and, in a third, waterproofing with a soap and alum solution was tried. The mixes were 1 : 1 : 2, 1 : $2\frac{1}{2}$: $4\frac{1}{2}$, and 1 : 3 : 6. Most of the concrete was of quaking consistency, although wet and dry mixes were also made. The specimens were well cured before submergence. After eleven years a careful examination of the piers indicated:

> 1, In the untreated specimens which were eroded on the surface most of the action occurred between the high and low watermarks;
>
> 2, the erosion in such cases was most pronounced on the faces and sides of the specimens;
>
> 3, evidence of the superiority of any one type of Portland cement is not furnished by an eleven-year exposure;
>
> 4, mixes containing hydrated lime or soap and alum were badly attacked throughout their submerged length, the pulverized clay mix was in fair condition;
>
> 5, 1 : 3 : 6 mixes are too lean even when very well mixed and of proper consistency;
>
> 6, a wet or a quaking consistency is much superior to a dry consistency, the 1 : 1 : 2 mixtures of wet consistency having withstood the attack very well (see *Engr. Record*, Vol. 69, p. 344).

Evidences of chemical attack of the Baltic Sea on the cement in large rubble concrete blocks of 1 : $2\frac{1}{2}$: 7 proportions were reported by W. Czarnowski in *Proc. I.A.T.M.*, 6th Congress, XVII_1. Although the alumina contents of the cements were normal, $6\frac{1}{2}$ per cent, analyses of material from the interior of the blocks after 11 years' exposure showed that a liberation of lime from the cement and an absorption of magnesia and sulphur trioxide had taken place.

Messrs. R. J. Wig and L. R. Ferguson wrote a valuable report based on examination of many structures situated along the coasts of continental United States (see *Engr. News-Record*, Vol. 79, pp. 532, 641, 689, 737, and 794). Their investigations may be summarized as follows:

1. Well-made plain concrete is durable in sea water provided it is properly placed and protected from erosion and abrasion. Plain concrete structures in northern latitudes are exposed to much more severe conditions than those built on the southern coasts.

2. The aggregate should be composed of tough particles so graded as to produce a hard, dense concrete. Enough water should be used to produce a placeable mix. Excess water is very harmful. Sea water can be used in gauging plain concrete, but should not be used when the work is reinforced and exposed to the air. In placing, great care must be taken to make the forms tight. Seams and porous spots must be avoided. If subjected to erosion or abrasion, surfaces above the low-water line must be protected. Walls and piers may be faced with stone. Piles may be protected by wooden fenders.

3. Reinforced concrete, when used above mean-tide level, is likely to disintegrate through corrosion of the reinforcement unless the latter is galvanized or protected by a considerably thicker shell of concrete than is now the current practice. Corrosion of reinforcement proceeds more rapidly in structures of the southern coasts than in those farther north where the water is colder.

547. Effect of Alkali Water.—In regions where alkali is present in the soil and ground waters, trouble has been experienced due to the disintegration of concrete and masonry structures. Waters running through such soil may contain as much as 1 per cent of alkali salts, the most destructive of which are the sulphates of magnesium and sodium, and the carbonate of sodium. Examinations of structures show that the most pronounced action occurs in portions of the masonry which are subjected to alternate wetting by the alkali solutions and drying by the air. Laboratory tests have shown that alkali salt crystals, which form very slowly, if at all, during the period of immersion, grow rapidly when the degree of saturation of the solution is increased by desiccation, and cause stress in the surrounding structure. If such crystals find lodgment in the surface of a porous substance, their expansion will break off portions of the material and gradually cause disintegration. When concrete or mortar is continuously submerged in alkali water the action is not marked.

Experiments have shown (see Art. 362) that certain cements, high in silica and low in C_3A, make concrete more resistant to alkali attack than others. Such cements in rich dense mixes should be used in alkali regions. When concrete conduits are used for alkali waters precautions must be taken both in placing and curing to secure a dense hard surface. If the concentration of alkali salts in the water is greater than 0.1 per cent, protective fabric coatings should be used, or suitable underdrainage should be provided to carry the alkali water away from the structure.

Many examples of the destructive action of alkali waters are cited in *Bulletin* No. 69, of Montana Agricultural College; *Bulletin* No. 132, of Colorado State Agricultural College, *Trans. A.S.C.E.*, Vol. 67, p. 572; *Technologic Papers* No. 12, 44, 95, 217, and 307, U. S. Bureau of Standards; also *Bulletin* No. 89, Engr. Expt. Sta., Ames, Iowa.

548. The Effect of Sewage on Concrete.—Whether concrete or mortar can be used in sewer constructions is dependent upon the character of the sewage. There are concrete sewers which have been in successful operation for many years, but there are also published accounts of others which have failed. If the sewage is of such nature that a strong odor of hydrogen sulphide is evolved, sulphuric acid will be formed with sufficient strength to attack the lime compounds of the concrete and produce disintegration.

Messrs. Barr and Buchanan * assert that the hydrogen sulphide is formed both by the bacterial decomposition of the sulphur containing proteins, and related compounds, and by the reduction of sulphates in the water supply. They found that the escaping hydrogen sulphide which is dissolved by the moisture on the walls above the sewage is oxidized, not alone by the air, but also by bacterial action. Examinations of septic tanks by these investigators showed that a soluble sulphur (SO_4) content in the raw sewage equal to 427 parts per million was sufficient to produce disintegration in a concrete dosing chamber. The disintegration of concrete sewers due to the above action always takes place above the water level. In the septic tanks investigated the action was particularly noticeable on the insides of the roofs. (See also *Engr. Rec.*, Vol. 61, p. 633.)

Acid effluents from pickling baths, wastes from creameries, or other acid wastes should not be discharged into concrete sewers until effectively diluted. For an example of the destructive action of pickling acid, see H. C. Webster's report on failure of the 29th St. Sewer in Milwaukee, Wisconsin.

549. Electrolysis of Concrete.—The disintegrations of certain reinforced concrete structures have apparently been due to electrolytic action of stray currents from neighboring power circuits. Studies of such action have been made by a number of investigators all of whom report that, under certain conditions, the integrity of a structure may be endangered. Probably the most exhaustive study of electrolysis in concrete has been made by the U. S. Bureau of Standards; its report is rendered in *Tech-*

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* *Bulletin* No. 26, Iowa State College.

nologic Paper No. 18, by Rosa, McCullum and Peters. In these experiments over four hundred specimens of the type shown in Fig. 27 were tested under voltages varying from 0 to 70. The test-pieces were made of 1 : 2½ : 4 concrete of Portland cement, sand, and broken stone. They were cured under damp sand after removal from molds for a period of twenty days, then they were placed in a damp closet until tested. The age of specimens when the tests were begun varied from a few days to about one year. The voltage was maintained continuously on some specimens for a period of over one year. Several different brands of cement were used, but the results showed no great difference in efficiency of corrosion for the normal American Portland cements. White Portland cement was inferior to the normal brands in resisting corrosion.

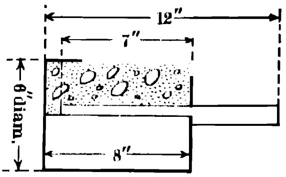

Fig. 27.—Type of Specimen Used in Electrolysis Tests.

The conclusions of these investigators may be partially summarized as follows:

1. Plain concrete is not affected by stray currents unless power lines are grounded in it.

2. A potential gradient of approximately 60 volts per foot was required to cause destruction of the test-pieces when the current flowed from the steel anode into normal wet concrete. With dry concrete the voltage required to produce disintegration was much higher.

3. The resistance of normal wet concrete rises rapidly with the length of time of passage of the current.

4. The use of salt in the mixing water is to be condemned, since it increases the conductivity of the concrete and thereby accelerates the corrosion of the reinforcement.

5. The splitting of the concrete surrounding a steel anode is caused by the oxidation of the steel. The volumetric increase of the steel due to oxidation was sufficient in a certain specimen to produce a radial stress of approximately 4700 lb. per square inch.

6. For a given number of ampere-hours and a given temperature, the amount of corrosion is independent of the current strength.

7. When the current flows for some time from the concrete to a steel cathode, the concrete is softened to a depth of ¼ in. or more around the reinforcement and the bond is destroyed.

8. Softening at the cathode occurs under much lower potential gradients than does the anode effect. Since in practice the steel may often be the cathode, danger from such effect is greater than from the anode effect.

9. The passage of the electric current from the concrete into the steel

causes a gradual concentration of sodium and potassium near the cathode. When concentrated, the attack of these alkalies is sufficient to soften the concrete and weaken the bond.

10. The danger from stray currents in practice, although well worthy of consideration, has been much overestimated.

11. By encasing concrete which is in contact with water in waterproof membranes, its resistance may be increased and the danger from electrolysis diminished. The electrical resistance of concrete foundations may also be materially increased by surrounding them with a shell of granite masonry.

12. Direct-current power circuits in concrete structures must be insulated from the ground. Pipe lines should be provided with insulating joints where they enter and leave a structure and lead covered cables should be isolated from the concrete.

TABLE 21.—THE SPECIFIC RESISTANCE OF CONCRETE AND MORTAR TO ELECTRICITY. (*Technologic Paper* No. 18)

Proportions................	Neat	1 : 2	1 : 4	1 : 2 : 3	1 : 2½ : 4	1 : 3 : 5	1 : 4 : 7
Resistance, in ohms per cm.^{3}	3500	2300	2100	6300	8000	8200	9900

13. When the metal within a building is insulated with respect to metal without, it may well be interconnected but it should never be grounded.

550. Specific Resistance of Concrete to Electricity.—Measurements of the specific resistance by the above investigators for mortars and concretes made of river sand and crushed trap rock gave the results in Table 21. The specimens were nine months old and had been soaked for three months previous to the test. Similar tests on granite and limestone rocks showed that limestone has six or eight times, and granite about a hundred times the resistance of the concrete tested. Consequently the character of the aggregate as well as the age, proportions, and moisture content will greatly affect the specific resistance of concrete.

CHAPTER XV

PORTLAND CEMENT PRODUCTS

551. General.—Within the past quarter of a century building blocks, brick, drain tile and sewer pipe made of Portland cement mortar or concrete have come into general use in construction. The use of these products has been especially large in regions where good aggregates and cement are obtainable at reasonable rates, and in regions where the cost of clay products is large due to freight charges. Furthermore, the wide distribution of suitable aggregates, the small cost of plant equipment, and the possibility of using unskilled labor are factors which have made these industries popular sources of investment for the man with little capital. These factors have had both a good influence and a bad influence on the growth of cement-product industries. They have been of advantage in promoting the widespread use of cement products, but great harm has been done the industries by the large quantity of poor material which has been turned out by incompetent manufacturers.

CONCRETE BLOCKS AND BRICK

552. Merits of Concrete Blocks.—By using hollow blocks it is possible to secure wall constructions which will be fireproof, dampproof and of low heat conductivity without sacrificing the strength of the structure. Concrete blocks can be made true in shape and dimensions and of such size that the maximum efficiency can be secured in laying a wall. In the latter respect they have a decided advantage over brick.

553. Types of Blocks.—Fig. 1 shows several types of blocks now on the market. All blocks excepting the one shown in Fig. 1*d* are 8 in. high. The block shown in Fig. 1*a* is much used in 8×8×16-in. and to less extent in 8×10×16-in. and 8×12×16-in. sizes. Occasionally blocks of this size, 8×12×24, are demanded but they are heavy to lay. Blocks like Fig. 1*b* are also considerably used in 8×8×16-in. sizes. For backing up brick or other facing material the narrow 8×4×16-in. block of Fig. 1*c* finds use. The block of Fig. 1*d* in 5×8×12-in. size is light and is favored by some because of the double air space.

554. Methods of Manufacture.—Concrete blocks are most economically made from a mixture of fine and coarse aggregate, although many good blocks are made without any aggregate larger than $\frac{1}{4}$ in. in diameter.

If coarse aggregate is used, it should all pass a $\frac{5}{8}$-in. mesh and be retained on a $\frac{1}{4}$-in. mesh. Gravel is preferable to broken stone because of the greater fluidity and density which it gives to concrete. In other respects the aggregates and cement should conform to the recommendations and specifications found in Ch. XIII and XII, respectively.

A natural aggregate for block and tile manufacture should be graded so that about one-third to one-half is coarse aggregate between No. 4 and $\frac{3}{8}$-in. sieves with the remainder a well-graded fine aggregate passing a No. 4 sieve. The fineness modulus can be built up to the values shown in Table 15, Ch. XIV, for the various types of aggregates. Although these data from Menzel's tests show that blocks of good strengths can be made in proportions as lean as 1 : 14, tests by Copeland and Carlson (*Proc. Am. Conc. Inst.*, Vol. 32, p. 485) show that walls made with blocks of 1 : 6 mix and leaner leaked in the rain test unless given two coats of paint on the exposed wall face. Therefore, if impervious units are desired, it seems unwise to use a mix leaner than 1 : 5 by volume. For severe exposures blocks 1 mo. old should have crushing strengths of 2400 lb./in.^{2} of net cross section. If faced blocks are made, the aggregate should be well-graded and durable and the mix should not be richer than 1 : $2\frac{1}{2}$ or 1 : 3 to insure against crazing. Machine mixing is preferable to hand mixing. With light-weight porous aggregates, premixing with water for two or more minutes is an effective way of eliminating too rapid withdrawal of water from the paste.

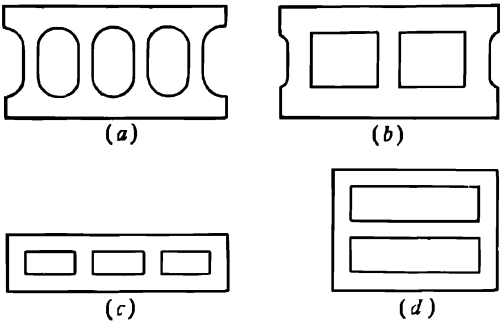

FIG. 1.—Common Types of Concrete Blocks.

Blocks are commonly consolidated in power tamper machines, although some hand-tamped units are still made. The vibrating table provides an effective means for producing dense units of relatively dry mixes. Excellent machines using this process are now on the market. Inasmuch as a deficiency in the amount of mixing water will cause a marked increase in the permeability of a block, it is of the utmost importance that all the water which the block can hold and still retain its shape after the mold is removed should be used. The use of an excessively dry mixture has been responsible for a great many poor blocks.

Blocks of slush consistency are poured into iron molds. By this process it is possible to secure a very dense block with a minimum amount of labor in molding, but it requires a very large outlay in molds.

No portion of the process of manufacture of concrete products is of more importance than proper curing. Advantageous ways of securing well-cured blocks are discussed in Art. 497.

555. The Testing of Blocks.—There are three rough field tests which can be made to determine the quality of concrete blocks: 1, the ring emitted when struck with a hammer; 2, the rapidity with which a dry block will absorb a bit of water poured upon its face; 3, the ease with which it can be scratched with a knife. A strong dense block will give a clear metallic ring, show little absorption and cannot be cut with a knife.

An excellent test of the imperviousness of a given concrete block wall can be made as follows: A wall four blocks long and four or five courses high is laid in neat cement mortar. A perforated pipe is suspended horizontally a few inches from the face and near the top of the wall. The pipe is then connected with a garden hose and the blocks subjected to a miniature shower. Observations should be made from time to time on the condition of the back of the wall. In tests made at the University of Wisconsin, walls of one-piece dry-process blocks wet through in many instances within an hour or two. Two-piece dry-process blocks and blocks of slush consistency withstood the test for several days.

With laboratory equipment the most important tests are: 1, crushing; 2, absorption. Fire tests and alternate freezing and thawing tests are also sometimes made. (See Art. 541 and 543.) The specifications of the American Concrete Institute follow:

STANDARD SPECIFICATIONS FOR CONCRETE BUILDING BLOCK AND CONCRETE BUILDING TILE *

Serial Designation: P-1-A-29

I.—General

1. The purpose of these specifications is to define the requirements for concrete building block and concrete building tile to be used in construction.

2. The word "concrete" shall be understood to mean portland cement concrete.

3. The average compressive strength of 3 or more concrete block or concrete building tile in lb. per sq. in. of gross cross-sectional area as laid in the wall shall not be less than 700 lb., no one unit falling below 600 lb. 28 days after being manufactured or when shipped.

Where ever concrete block or building tile are used to carry unusual heavy loads, the average compressive strength of 3 or more of these units 28 days after being manufactured or when shipped in lb. per sq. in. of gross cross-sectional area as laid in the wall shall be at least 10 times the figured superimposed load to be applied.

Non-load-bearing concrete block and concrete tile shall have sufficient strength necessary to prevent excessive breakage during delivery and handling.

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* Adopted as Standard Specifications, February, 1929.

4. The gross cross-sectional area of a one-piece concrete block or tile shall be considered as the product of the length times the width of the unit as laid in the wall. No allowance shall be made for air spaces in hollow units. The gross cross-sectional area of each unit of a two-piece block or tile shall be considered the product of the length of the unit times one-half the thickness of the wall for which the two-piece block or tile is intended.

5. The compressive strength of the concrete in units of all classifications except "non-load bearing block" shall be at least 1000 lb. per sq. in., when calculated on the minimum cross-sectional area in bearing.

6. Concrete Building Block and tile to be exposed to soil or weather in the finished work (without stucco, plaster or other suitable protective covering) shall meet the requirements of the absorption test.

7. All concrete building block and tile not covered by Paragraph 6 need not meet an absorption requirement.

8. Concrete block and tile shall not absorb more than 10 per cent of the dry weight of the unit when tested as hereinafter specified, except when it is made of concrete weighing less than 140 lb. per cu. ft. For block or tile made with concrete weighing less than 140 lb. per cu. ft. the absorption in per cent by weight shall not be more than 10 multiplied by 140 and divided by the unit weight in pounds per cubic foot of the concrete under consideration.

9. Specimens for tests shall be representative of the commercial product of the plant.

10. Not less than three and preferably five specimens shall be required for each test.

11. The specimens used in the absorption test may be used for the strength test.

II.—Methods of Testing

12. The specimens shall be immersed in clean water at approximately 70 deg. F. for a period of 24 hours. They shall then be removed, the surface water wiped off, and the specimens weighed. Specimens shall be dried to a constant weight at a temperature of from 212 deg. to 250 deg. F. and re-weighed. Absorption is the difference in weight divided by the weight of the dry specimens and multiplied by 100.

13. The weight per cubic foot of the concrete in a block or tile is the weight of the unit in pounds, divided by its volume in cubic feet. To obtain the volume of the unit fill a vessel with enough water to immerse the specimen. The greatest accuracy will be obtained with the smallest vessel in which the specimen can be immersed with its length vertical. Mark the level of the water, then immerse the saturated specimen and weigh the vessel. Draw the water down to its original level and weigh the vessel again. The difference between the two weights divided by 62.5 equals the volume of the specimen in cubic feet.

14. Specimens for the strength test shall be dried to constant weight at a temperature of from 212 deg. to 250 deg. F.

15. The specimens to be tested shall be carefully measured for overall dimensions of length, width and height.

16. Bearing surfaces shall be made plane by capping with plaster of paris or a mixture of $\frac{1}{2}$ portland cement and $\frac{1}{2}$ plaster of paris, which shall be allowed thoroughly to harden (from 3 to 6 hours) before the test. No point on the surface shall deviate from the plane more than 0.003 in. The cap shall not be thicker than $\frac{1}{8}$-in. It shall be formed by means of an accurately machined metal plate or a heavy plate glass having a true surface.

17. Specimens shall be accurately centered in the testing machine.

18. The load shall be applied through a spherical bearing block placed on top of the specimen. The rate of loading after 50 per cent of the ultimate load has been applied shall not be greater than that which will produce a shortening of the specimen of 0.02 in. per minute.

19. When testing other than rectangular block or tile care must be taken to see that the load is applied through the center of gravity of the specimen.

20. Machined-steel or cast-iron plates of sufficient thickness to prevent appreciable bending shall be placed between the spherical bearing block and the specimen. In no case shall the distance between the edge of the spherical bearing block and the end of the bearing plate be greater than twice the thickness of the plate. Where a number of thin plates are used, in no case shall the plates be less than one inch thick nor shall any plate extend beyond the one immediately above it a greater distance than twice the thickness of the plate.

21. The specimen shall be loaded to failure.

22. The compressive strength in pounds per square inch of gross cross-sectional area is the total applied load in pounds divided by the gross cross-sectional area in square inches.

556. Concrete Brick.—In localities where a good coarse sand is found and cement is cheap, brick may be made of cement mortar which can successfully compete with clay building brick. One of the merits of concrete brick is the true shape. Furthermore it is possible to make special shapes and sizes to exact dimensions almost as cheaply as the standard sizes.

For body brick an economy may be effected by adding coarse aggregate to the mix. The same considerations should obtain in determining proportions for concrete brick as for concrete blocks. Mortar or concrete for brick making should have a strength of 1800 lb. per square inch at an age of one month when tested in the form of a prism or cylinder with a height equal to twice the diameter. Good concrete brick one month old should have a modulus of rupture under transverse test of 450 lb. per square inch; half brick, at the same age bedded flatwise should have a compressive strength of 2500 lb. per square inch. Good concrete brick should not absorb more than 6 per cent of water. The methods of testing used for clay brick can be applied to concrete brick.

CEMENT DRAIN TILE AND SEWER PIPE

557. The Advantages of Cement Pipe.—Besides having the advantages common to other cement products cement pipe possesses two additional merits. They can be made true to form and of circular, oval or any desired cross-section. Furthermore, it is possible, by regulating the thickness of the shell or by reinforcing with steel, to make the pipe strong enough to withstand the pressure due to any superimposed ditch filling. Indeed reinforced pipe are being used for pressure conduits.*

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* The description of a long 36-in. pipe line under 70 ft. head may be found in *Eng. News*, Vol. 68, p. 248.

558. Method of Manufacture.—Portland cement of standard quality and a well-graded sand containing a large proportion of coarse particles are generally used for making the smaller sizes of tile or pipe. The proper proportions vary with the nature of the aggregate. For ordinary bank sands it is not safe to use a mix leaner than 1 : 3. With exceptionally good aggregate the proportions may be increased to 1 : 4. If the tile is to be laid in an alkali soil, only the best of sands should be used and the proportions should not be leaner than 1 : 3.* In making the larger sizes of drain tile and sewer pipe, it is good practice to employ concrete having a maximum size of coarse aggregate not over one-third of the thickness of the pipe wall. The mix should contain sufficient mortar so that a dense product can be secured. Proportions may vary from 1 : 2 : 3 to 1 : 2½ : 4, depending on the nature of the fine and coarse aggregates. The use of pit run gravel or run of crusher stone should not be permitted on account of the variation in the gradation of the aggregate.

In mixing, both machine and hand methods are used. Either is satisfactory when properly done (see Art. 489 and 490), but the machine mixing is far more economical. The consistency of the mix should be as wet as possible without interfering with the immediate removal of the molds. When the proper consistency is employed a web-like marking will be produced on the surfaces of the pipe. This is entirely lacking on products made from dry mixes.

In the larger plants the tile or pipe are filled and tamped by machines, of which there are two main types—the spiral-tamping machines and packer-head machines. In the former the mold is centered upon a horizontal table revolving about a vertical axis, and the mix is spouted into it. Tamping is accomplished by blows from a slender plunger which is moved up and down four or five hundred times a minute while the tile is being revolved. In some machines the plunger is held by a friction grip so that its length can be automatically shortened as the mold is filled without changing the intensity of the blow.

With the packer-head machines the molds have no inner lining and are stationary. The packer-head revolves about a vertical central axis and also has an up-and-down motion. The head itself consists of a smooth cylindrical iron disc about 4 in. long and of the same diameter as the inside of the tile. It is surmounted by a set of adjustable radial vanes. In operating, the head is run to the bottom of the mold and the feeding spout opened. As the head is raised the material is forced outward against the mold by centrifugal force and the interior of the tile is finished by the troweling action of the outer portions of the vanes and the disc.

Tamping machines operate more slowly than the packer-head devices, but they produce a more uniform pipe. For these reasons cement drain tile are generally made by the packer-head method, while cement sewer pipe are made by tamping machines.

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* See *Technologic Paper* No. 44, U. S. Bureau of Standards, entitled *Investigation of the Durability of Cement Drain Tile in Alkali Soils*.

The method of curing outlined in Art. 497 should be followed if good results are to be secured. Nearly all plants now expose the tile to an atmosphere of wet steam for at least thirty-six hours, the temperature being kept above 70° F. The steam should be saturated so that condensation is in evidence on the walls of the curing chamber and on the product. Dry steam even at a high temperature will generally do more harm than good. After steam curing the pipe or tile should not be subjected to a temperature below 40° F. before they are two weeks old. To secure an impervious product it is necessary to sprinkle the pipe twice a day for at least one week after removal from the steam, especially if the weather is warm and the humidity low.

559. The Testing of Cement Pipe.—The rough field tests mentioned in Art. 287 may also be used to determine the quality of drain tile or sewer pipe. Many plants and most laboratories make absorption and crushing tests to ascertain quality. Both of these tests are made in the same manner as described in Art. 291 and 293. Fragments of cement drain tile or sewer pipe should not absorb over 8 per cent of water, by weight. The table in Art. 324 shows the bearing strengths per lineal foot which the different sizes and classes of drain tile and sewer pipe should carry. A method for making feezing tests on drain tile appears in Art. 296.

Good concrete sewer pipe should be capable of carrying an internal water pressure of 15 lb. per sq. in. for 15 minutes when subjected to test (see A.S.T.M. specifications).

MISCELLANEOUS CONCRETE PRODUCTS

560. Poles, posts and piles are also cast or formed by centrifugal processes out of concrete. In most cases these forms must be reinforced to withstand flexure. The material is well adapted to use in posts and poles, but reinforced piles exposed to sea water are likely to suffer from corrosion of the reinforcement in the sections above high-water level. Reinforced concrete railroad ties have also been tried but without much success, the material being too brittle for such purposes.

561. Cast Stone and Other Forms. *Cast Stone.*—Since the World War a considerable impetus has been given to the manufacture of artificial stone produced from Portland cement and specially prepared aggregates for facing and trim on buildings and other structures. Cast stone usually is made either from a relatively dry mix and tamped into molds (dry tamped stone) or from a mix which will flow sluggishly into place in the molds (wet cast stone). Sand, plaster of paris, glue, wood, or steel molds are used for various kinds of products. Sand or plaster molds may be used to effect a reduction in the water-ratio of the mix prior to hardening. Beautiful shades and textures are evolved from combinations of white cement, colored aggregates and mineral pigments. The finished surface is commonly produced by cutting, by etching with an acid, or by rubbing on a revolving cast-iron table.

Tests on specimens from fifty-eight varieties of cast stone made by Tucker and Walker of the Bureau of Standards (see *Proc. A. C. I.*, Vol. 29, p. 501) show that over half of the samples exhibited crushing strengths of 5000 to 8000 lb. per sq. in. and, after drying to constant weight at 110° C. and soaking 24 hours in distilled water at 21° C., absorptions of 5 to 8 per cent. Many of the stronger samples were in good condition after being subjected to 300 cycles of freezing.

Other Forms.—On account of the readiness with which concrete can be cast and modeled it forms an inexpensive material out of which the artist creates a great variety of handsome ornamental forms for the decoration of structures. Artistic urns, fountains, benches, and pieces of statuary molded out of concrete adorn many of our lawns, parks, and drives. Although the making of ornamental concrete is a comparatively new industry, yet the general characteristics of the material and the durability of the work thus far done, indicate an increasing demand for such products.

CHAPTER XVI

METALS AND THEIR ORES

562. Metallurgy Defined.—Metallurgy may be defined as the art of extracting metals from their ores, and their subsequent adaptation to the uses of man. As a division of engineering practice, the field is intermediate between those of the mining geologist and engineer, who exploit nature's deposits and take out the ores of value, and of the civil, electrical, and mechanical engineers, who are concerned with the fabrication of the metal into the finished structure or machine.

As implied in the definition, the field of metallurgy is broadly divisible into two parts: The recovering of the metal from the comparatively crude or complex forms in which it is taken from the ground; and the further manipulation or treatment of the metal, relatively pure or otherwise, to fit it to withstand best the varying conditions of service. To the user of materials the latter is in general the more interesting and important division of the art.

563. The Metals of Construction.—The metals used in considerable quantities in engineering construction are comparatively few in number: iron, copper, lead and zinc may be considered as the primary; and aluminum, tin, nickel, antimony, silicon, manganese, vanadium, chromium and tungsten, as the important metals of secondary rank. That is, the first four are usually the base metals in materials of construction, and are almost essential in engineering practice; the secondary metals are in general not so essential, or have their principal use because of their modifying influence when used in mixture with the metals of the primary division.

564. The Utility of the Metals in Construction.—The utility of any metal depends upon its adaptability and workability and upon its cost. The two first named are functions of the physical properties of the material; the cost depends upon the abundance and accessibility of the metal, its form of occurrence, and the ease of extraction and treatment. The properties of importance in metals for construction purposes are: tenacity, elasticity, ductility, malleability, hardness, specific gravity, fusibility, viscosity, color, corrodibility, expansibility, conductivity (electrical and thermal) magnetic quality, electrical potential, and frictional quality.

Iron is by far the most important of the metals used in engineering construction. It is very abundant in nature, which fact, together with the accessibility of the deposits and the comparatively low cost of extraction, makes it a cheap metal. The value is about $\frac{3}{4}$ to 1 cent per pound in the form of pig iron, which may be considered as the raw material for the manufacture of the shapes used in construction. Production in the United States has now reached upwards of 35 million gross tons per year, valued roughly at $730,000,000. This is about one-third of the yearly production of the world. Pure iron is relatively soft, very ductile, and of moderate tensile strength—40,000 to 50,000 lb. per square inch. The specific gravity is 7.9, and the melting-point 1530° C. The ready corrodibility of iron in the atmosphere and otherwise is a disadvantage; and in many places it is used only because its cheapness, coupled at times with advantageous properties, is a factor sufficient to offset the inevitable decay. Iron possesses magnetic properties vastly superior to any other metal, and it would therefore find extensive use in certain fields, regardless of the development of substitutes for many of its present uses. Iron owes its greatest utility to the fact that it alloys freely with other elements, and its inherent properties are markedly altered and improved for varying conditions of service. Practically all of the iron and steel used in engineering construction has purposely had added to it varying proportions of different elements, and it will therefore receive consideration with the alloy group.

Copper is a very important metal. The United States in 1937 produced 834,661 net tons, about 35 per cent of the world's output. Consumption of copper in this country in 1937 was 860,000 net tons, of which about 55 per cent went into copper wire and rods; 22 per cent into sheets, strips, tubes, and castings; and 23 per cent into brass and other copper alloys. Nearly 50 per cent was used for electrical purposes, 13 per cent in automobiles, 8 per cent in building construction, and 5 per cent in bearings, bushings, valves and pipe fittings. Copper is soft and ductile, being somewhat like pure iron in this respect. Its specific gravity is 8.9, and the melting-point 1065° C. Its relatively high cost, varying from 10 to 20 cents per pound, limits its use to those places where its inherent advantages make its employment necessary. Copper is especially immune to corrosion in the atmosphere, and has an exceptionally high electrical conductivity, being slightly surpassed only by silver. It alloys very freely with other metals, particularly zinc and tin, to form brass and bronze

Lead is of service in the arts because of its softness, ductility, plasticity, low fusion point, and non-corrodibility. It has very low strength, a specific gravity of 11.3, and melts at 327° C. It is a metal of moderate cost, varying from 4 to 7 cents per pound in different years. Production in the United States in 1937 was 621,817 short tons, or about 35 per cent of that of the world. About 23 per cent of the lead consumed was made into white lead and oxides; 31 per cent was used in storage batteries;

15 per cent for cable covering; 7 per cent in building construction; 9 per cent for bearing metal, type metal and solder; 6 per cent for ammunition; and 4 per cent in foil.

Zinc is a metal of low tensile strength—7000 to 8000 lb. per sq. in. —and is rather brittle. It becomes sufficiently ductile at about 100 to 150° C. to be rolled into sheet form. The specific gravity is 7.1 and the melting-point 420° C. The cost varies normally from 5 to 9 cents per pound. United States' production in 1937 was 626,336 short tons, or about one-third of the world's total. The property of zinc which renders the metal most useful is its resistance to atmospheric attack. About 10 per cent finds outlet as sheet zinc, and 42 per cent for the galvanized protective surface of steel sheets, tubes, wire, and shapes. Zinc forms with copper the useful alloy brass, and about 28 per cent of the total consumption is for that purpose. Miscellaneous uses in die castings, alloys and otherwise, account for the remaining 20 per cent.

Aluminum is the most important secondary metal and has many useful properties. It is non-corrodible in the atmosphere, has good color, is easily workable, has good strength and ductility, and is especially serviceable because of its low specific gravity and high electrical conductivity. Only the high cost of the metal due to difficulties in extraction, coupled with poor welding quality, prevents a much wider range of application, and in many cases of substitution for metals now commonly employed. The specific gravity is 2.58, and the melting-point 657° C. The tensile strength is about 17,000 lb. per square inch in the cast form and 35,000 lb. per square inch when drawn into wire. Production in the United States for 1937 was about 146,000 short tons. The cost is from 18 to 25 cents per pound. The greater part of the aluminum is used where light weight is essential, probably half of it in the pure form, and the other half alloyed with moderate amounts of other metals to confer added stiffness or other useful properties without great increase of specific gravity in the resultant metal. About 20 per cent is used in transportation.

The other secondary metals are used mainly in mixture with the iron, copper, lead, or zinc, to alter or improve their normal properties. Considerable proportions of the nickel and tin, however, are employed to form ornamental or rust-resistant coatings for objects made from the other metals, especially iron.

565. Ores.—One of the important divisions of the field of metallurgy is the winning of the metals from their ores. The ore is the form in which the metalliferous mineral occurs in the earth, and from which it may be commercially extracted. The metal which it is sought to recover may be present in the native or metallic form, but usually exists as a compound of the metal with other elements; associated with the metalliferous mineral is a varying amount of earthy matter, called the gangue.

The following are the most important chemical combinations in which the more common metals are found:

Oxides or hydrated oxides—iron, copper.
Sulphides— copper, lead, zinc.
Carbonates— lead, zinc, iron, copper.
Native— copper (silver, gold).
Silicates— zinc.
Chlorides— lead.

566. Economic Value of Deposits.—Whether or not a metalliferous deposit is an ore depends upon economic considerations. The commercial feasibility of recovery depends upon:

(1) Nature of the metal—the more valuable the metal to be recovered, the greater the extremes to which one may go in such recovery, and still show a profit in the operation.

(2) Richness of the deposit—the greater the percentage of metal present in the deposit, the more feasible is the prospect of extraction; other things equal. A deposit with 50 per cent of iron content is high grade, while one with 30 per cent is lean. Copper ores, on the other hand, vary from 5 to 1 per cent in the largest workings of this country. The average amount of gold recovered from straight ores in the United States in 1936 was valued at $5.17 per ton, indicating a yield of approximately $\frac{1}{7}$ oz. per ton or 0.0006 per cent.

(3) Association—two or more metals may be associated in an ore, and recovery of both will show a net profit, whereas if the separate metals were alone in their individual proportions extraction would not be feasible. Very great values in silver are recovered in lead extraction from certain ores, although the percentage content is so low in many cases as to be apparently negligible. Most of the nickel is obtained from ores where it is associated with sufficient copper to warrant recovery of both metals. Certain iron ores have an added value conferred by the association of nickel or manganese. Again the association may not be of a metallic nature, but may, even as part of the gangue material, save additions in the extraction process, and in consequence warrant the treatment of otherwise too lean ores. Thus the lime associated with some European and Southern ores enhances their value. On the other hand, foreign substances of a detrimental nature may be present in the deposit, and either destroy the possibility of economical recovery or so increase the costs of the operation as to lower the grade of an otherwise rich ore. High phosphorus in iron ores, or the high titanium content of many of the iron deposits of New York, are instances in point.

(4) Situation—Geographical location with respect to facilities for transportation, and accessibility to smelting centers and markets for their

products are factors for consideration. Immense deposits of rich iron ores in Brazil are practically untouched at the present time because of transportation difficulties and costs. Again, location of the deposit with respect to ground surfaces, as determining the methods and cost of mining, is an item in the determination of its value. Finally, extent of the deposit, both as to total quantity and character of distribution, is an important factor. To warrant exploitation, an iron deposit must have large tonnages in sight in a bedded form of considerable thickness. The more valuable the metal, the more feasible it becomes to take out the mineral occurring in veins, pockets, or streaks.

(5) State of the art—cheaper methods of extraction may be developed which will show a profit in the recovery of metals from ores of too lean a character to be treated by present-day methods; or such processes may eliminate some element now detrimental. Also as the high-grade ores become exhausted it becomes necessary to draw upon sources of supply of less rich character, or at more remote or inaccessible places.

567. Preparation of Ores for Extraction of Metals.—After the ore has been mined, it is usually necessary to prepare it for the extraction process, by some method of ore dressing or concentration. The object is to get rid of some harmful constituent or some of the gangue material by a method depending upon different physical or chemical properties than those of the extraction operation, and accomplishing the result in a more effective and economical manner. Naturally the greater the intrinsic value of the metal to be recovered, the greater is the amount of ore dressing which can be employed, other things being equal. On account of the fact that it is usually more feasible to extract the metal at a place favorably situated with respect to fuel, etc., and remote from the mine mouth, elimination of a considerable portion of the gangue at the mine will minimize transportation of such useless material, and such saving will often more than repay the cost of concentration aside from the advantages resulting from a material more favorable for extraction.

Concentration methods usually begin with a crushing and sizing of the ore to a point as close as economical considerations will warrant, to the theoretical limit of mechanical disintegration of the useful mineral from the gangue. Varying physical or chemical characteristics of the two are the basis for the separation. Washing with water will carry away clays or substances which will form an emulsion or go into solution. Specific gravity differences will enable one to effect a separation by flotation in water, oil, etc., usually by some means of controlling its velocity of flow or pulsation. Magnetic separation is often of value, particularly when iron minerals are present.

568. Principles of Extraction of Metals.—Metallurgical extraction methods are divisible into two groups: Wet methods involve solution of the metal sought, and recovery by precipitation; while useful in some fields, particularly gold and silver, they are relatively unimportant in the metallurgy of the metals used in engineering construction. Dry methods predominate; usually called smelting, and effected with the aid of heat. After the ores have been properly prepared for treatment, the smelting operation consists essentially of a reduction of the metal from its chemical combination in the mineral, a fusion of the metal and the gangue as slag, with recovery of the metal. The result may be obtained in one operation and furnace; or it may require several to properly fit the metal for use in the arts.

The chemical reactions involved in the recovery of the metals in smelting are mainly oxidation with air, metallic oxides, and carbon dioxide; and reduction by means of carbon, carbon monoxide, hydrogen, sulphur, or certain metals.

Heat is often employed preliminary to smelting, to effect a change in the chemical nature of the mineral or ore, without fusion or reduction to the metallic form. Drying, calcination, or roasting involve the driving off of the moisture, the dissociation of hydrates or carbonates with elimination of water or carbon dioxide, and the removal of sulphur by oxidation and volatilization as sulphur dioxide.

CHAPTER XVII

REDUCTION OF IRON FROM ITS ORES

569. The Economic Importance of Iron and Steel.—The iron and steel industry has had its principal development in the United States and Europe. Production of pig iron in recent years is shown in Table 1.

TABLE 1.—QUANTITY AND VALUE OF PIG IRON PRODUCED IN LEADING COUNTRIES OF THE WORLD

Country.	1905		1915		1937	
	Long Tons.	Dollars.	Long Tons.	Dollars.	Long Tons.	Dollars.
United States	22,992,380	382,450,000	30,384,486	401,409,604	36,145.095	731,139,435
Germany	10,814,018	....	11,603,914	....	15,700,000	
Great Britain	9,592.737	....	8,793,659	....	8,350,000	
France	3,028,383	....	4,674,950	....	7,800,000	

Production in Russia has grown rapidly and now exceeds that of Great Britain. In addition, Belgium, Japan, India, and Australia produce considerable pig iron. By far the greater proportion of pig iron produced in the United States is made from domestic ores, although there is a considerable tonnage of ore imported from Chili, Cuba, Sweden, Norway, Russia, and Canada to supply seaboard furnaces. Germany is largely dependent upon iron ores obtained from beyond her borders. Her chief supplies are from the Lorraine fields, extending into Luxembourg, Belgium, France, and Germany. Great Britain has important deposits of iron ore on her northeast and northwest coasts, but obtains about one-third of her supply from foreign fields.

570. The Native Sources of Iron Ores.—Iron ores are mined in many states of this country. There are three great producing districts: Lake Superior, centering about the head of that lake in Minnesota, Michigan, and Wisconsin; Southern, chiefly in Alabama, near Birmingham; and Eastern, largely in Pennsylvania, New York, the Adirondacks region, and New Jersey. Additional tonnage is obtained from Wyoming, Utah, California, Tennessee, and New Mexico. The Lake Superior district produces about four-fifths of the annual tonnage of this country. Southern ores are smelted largely in the vicinity of the mines. New York ores find outlet locally and in eastern Pennsylvania furnaces; while almost all of the Lake Superior ore is shipped from 600 to 1000 miles to smelting centers. The greatest proportion is sent to lower Lake Erie ports for transshipment by rail to furnaces in the Pittsburgh districts; while a considerable tonnage is smelted in the region centering about Chicago. The Pittsburgh district has long held the supremacy as the steel-making center of the United States, largely because of the economic advantages of good fuels (coal, coke, natural gas and oil) and accessibility to the consuming markets. With the trend of population westward, and the changed conditions due to the development of modern coking processes, it is likely that Chicago will become an increasingly greater center of activity. Production in Colorado or far western districts will be entirely to satisfy local demands.

571. Classes of Iron Ores and Their Characteristics.—The ores of iron are classed according to the iron mineral which is predominant. They are, in the order of theoretical percentage of iron content in the mineral:

Magnetite; Fe_3O_4—72.4 per cent iron. It is steel gray to black in color; very hard and strongly magnetic. Magnetite is not a very prominent ore in the United States, but is mined to a considerable extent in Pennsylvania and New York. There are large tonnages in New York which are not exploited at the present time because of associated titanium, which causes difficulty in smelting. Magnetite is the important ore of Sweden, where it is of high purity.

Hematite; Fe_2O_3—70 per cent iron—is red to brown in color, and occurs in some deposits in a hard, lumpy condition, whereas in others it is soft and of fine texture. Hematites form the principal ores of the United States; the ore of Lake Superior and much of that of the South is of this character. Hematites are also important in the west of England, Spain, Cuba, Chile and Africa. Immense deposits of high grade ore exist in Brazil, but have not been exploited to any extent as yet because of transportation difficulties.

Limonite; $2Fe_2O_3+3H_2O$—59.9 per cent iron, 14.5 per cent water of combination. This is a hydrated hematite, is soft and of a yellow color. It becomes red hematite by dehydration at high temperature. By partial dehydration, ores of brown color, called brown hematites, result. These are prominent in the southern deposits of the United States, and in the Minette district on the German-French border. Limonites are important in the Cuban deposits.

Siderite; $FeCO_3$—48.3 per cent iron, 41.4 per cent CO_2—also called spathic ore. The principal deposits are in Germany and Austria, in Wales and the northwest district of England. Normally the ore is hard and stonelike with a gray color, but is often associated with clay or carbonaceous matter, and in the latter case the color is black or streaked with black. Carbonate ores were formerly important in Pennsylvania.

While iron silicates and sulphides are plentiful in nature, they are of no importance at the present time as ores.

Iron ores occur in all conditions in nature, from hard ores requiring blasting, to soft ores which can be mined directly with steam shovels. Successfully mined deposits are often thousands of feet below the surface of the ground, and again may be so close to the surface as to be capable of open cut mining after a variable amount of stripping of top soil.

The relative production of the various iron ores in the United States during recent years is given in Table 2.

TABLE 2.—RECENT PRODUCTION OF IRON ORE IN THE UNITED STATES

Kind of Ore.	1905		1915		1937	
	Long Tons.	Per Cent.	Long Tons.	Per Cent.	Long Tons.	Per Cent.
Hematite *	37,567,055	88.3	52,227,324	94.1	68,072,781	94.4
Brown ore †	2,546,662	6.0	1,488,709	2.7	666,374	0.9
Magnetite	2,390,417	5.6	1,807,002	3.2	3,353,861	4.6
Carbonate	21,999	0.05	3,455	0.006	532	
Total	42,526,133	100.00	55,526,490	100.00	72,093,548	100.00

* Anhydrous sesquioxide.

† Hydrated sesquioxides.

572. Elements Associated with Iron Ores.—Typical analyses of iron ores are given in Table 3.

The iron content in different ores varies considerably; values range from 30 per cent to upwards of 50 or even 60 per cent. The Lake Superior ores are very rich, while those of the South are comparatively lean. Many ores, and this is true of certain of the southern deposits, have the disadvantage of the lean iron content offset to a degree by the association of lime, alumina and silica in proper proportions to be self fluxing, thereby forming suitable slags without purchase of the necessary flux (usually limestone) to ensure fluidity. The gangue is earthy material, of which the principal constituents are usually silica and alumina. Increasing amounts of such gangue lower the value of the ore by decrease of iron content and corresponding increase of handling, fuel, and flux costs per ton of pig iron. Alkalies or basic constituents may have the offsetting advantage of decreasing the amount of flux required in smelting. Sulphur and phosphorus are always present in varying degree in iron ores. Up to 1 per cent of the former may be successfully removed to the required limits in blast furnace smelting, but requires increased fuel and flux; thus increasing sulphur lowers the value of the ore. Phosphorus, on the other hand, is eliminated only by special processes in the refining of the crude blast furnace product to steel; the necessity of such selection of a more

TABLE 3.—CHEMICAL ANALYSES OF VARIOUS IRON ORES

(From *Tenth Census Reports*, Vol. 15)

Components.	Kind of Ore.						
	Hematite.			Limonite		Magnetite.	**Carbonate.**
	25.	538.	252.	267.	967.	738.	995.
Fe	62.65	59.52	50.04	53.60	44.60	48.91	43.05
P	0.011	0.005	0.108	0.641	0.365	0.015	0.115
S	0.018	0.020	0.179	0.085	0.011	0.548	0.045
FeO	1.81	0.78	0.22	0.46	....	21.99	54.385
Fe_2O_3	87.47	84.16	71.15	75.99	63.714	44.75	1.071
SiO_2	4.12	12.17	11.23	10.52	....	12.18	
Al_2O_3	2.37	2.21	4.99	5.58	1.090	0.79	1.457
MnO	0.25	......	......	0.23	....	0.10	3.254
Mn_2O_3	......	......	......	......	0.455		
CaO	0.26	0.04	0.25	2.23	0.180	3.10	0.540
MgO	1.58	0.04	0.25	0.52	0.324	11.72	0.540
FeS_2	0.034	......	0.337	0.124	....	1.031	
BaO	......	0.10					
CoO	......	......	......	......	....	......	0.010
Co_2O_3	......	......	......	......	0.040		
SO_3	......	0.05	......	0.05	0.027	......	0.112
K_2O	0.38	0.15	0.14	0.17			
Na_2O	......	0.07	0.11	0.01			
P_2O_5	0.26	0.011	0.246	1.469	0.836	0.34	0.263
CO_2	0.12	0.04	0.13	0.09	....	0.40	35.340
C	0.01	......	0.25	0.04			
H_2O (Hygr.)	0.19	0.12	0.42	1.02	11.980	0.29	0.923
H_2O (com.)	1.12	0.37	10.20	1.69		3.79	by dif.
Insol. res	......	......	......	......	21.940	......	2.105
Total	100.40	100.311	99.923	100.193	100.586	100.175	100.000
Sp. gr	4.534	......	3.706	4.110			
Locality	Chapin	Pilot Knob	Tecumseh	Attala	Hellertown	Tilly Foster	Hellertown
State	Mich.	Mo.	Ala.	Ala.	Pa.	N. Y.	Pa.

costly method means that phosphorus content greater than 0.05 per cent in an ore carrying 50 per cent of iron, has a marked effect in lowering the value. Phosphorus of 0.001 per unit of iron is the limiting content dividing iron ores into the two great divisions of Bessemer and non-Bessemer. All good steel must not exceed 0.10 per cent of phosphorus; the elimination of any excess costs money, and the presence of such excess in the ore lowers the grade.

573. Preliminary Treatments for Iron Ores.—Iron ores usually undergo no treatment preliminary to smelting; except carbonates, which are calcined to drive off the carbon dioxide. Sulphur in excess of that suitable for economical smelting can be lowered by roasting and volatilization as sulphur dioxide. Much of the magnetite mined in New York is crushed and treated by magnetic separation, whereby a considerable proportion of the non-magnetic gangue and phosphate constituents are removed, and two-fold enrichment in grade is the result. Washing of the brown ores of the South is practiced to remove excessive clay, and this method is coming into increasing importance to remove sand and clay from certain of the Lake Superior ores. Drying of ores is necessary in many cases, and is attracting more and more attention; elimination of excessive moisture results in increased smelting economies, and in addition the cost of drying may be more than compensated for by the saving in freight charges on the water content. Agglomeration of fine ores by briquetting with binders of slag, tar, etc.; or nodulizing or sintering by partial fusion, are being successfully practiced. At present the employment of these methods is chiefly in the utilization of flue dusts formed in blast furnace operation.

574. Fundamental Principles of Extraction of Iron.—The fundamental chemical principles in the extraction of iron from the ores are very simple. Heating the ores in the presence of a reducing agent (usually carbon or carbon monoxide) will result in the formation of carbon monoxide or carbon dioxide, liberated as a gas, and metallic iron. Reduction of red oxide of iron, Fe_2O_3, by carbon monoxide will begin at temperature as low as 200° C., and proceed by progressive formation of Fe_3O_4, FeO and Fe. Reduction to metallic iron is practically complete at temperature as low as 800° C. very much below the fusion point of iron, which melts at 1530° C. when pure, and may have its fusion point lowered to 1150 or 1200° C. by the presence of associated elements or impurities.

575. Ancient Methods of Extraction.—This ready reducibility of iron oxide to metallic iron at moderate temperatures was the basis of the ancient methods of manufacture with apparatus of the simple hearth or forge type, resembling a crude blacksmith's forge, and with such forced draught only as could be obtained from bellows, in many cases hand-operated. A small charge of ore together with the necessary charcoal for fuel and reduction were heated for a sufficient time to effect reduction of the iron to a pasty mass. Ores of a minimum of associated gangue material were selected, much of which could be eliminated by combination with iron oxide to form a slag of fairly low fusion point, but necessarily with considerable loss of iron in the slag. The resultant mass of spongy iron with its entrained slag, was taken from the forge and hammered to a rough bloom or bar. Much of the slag was thus eliminated by pressure; but, just as it is impossible to eliminate all of the moisture from a sponge by squeezing, so it was impossible to squeeze out all of the slag. The product of the forge was a malleable material with varying amounts of occluded slag which was extended by forging into long filaments; a product identical in physical structure with the wrought iron of more modern times.

576. Direct and Indirect Methods of Producing Ductile Ferrous Metals.—Since for the larger part of the iron which is used in the arts, some degree of its inherent malleability and ductility are desired, any process of manufacture whereby the product is obtained in this condition in a single operation represents the ideal. The " direct process " still makes its appeal to the inventor; actually, however, the amount of product so produced is negligible in a consideration of the annual tonnage. Unfortunately, such processes have many disadvantages; intermittent character, inefficient types of furnace, high labor costs, and large losses of iron in the slag. And especially, because detrimental impurities such as sulphur and phosphorus are only removed, or most economically so, in processes which bring the products to fusion, and where slags of special composition and volume can be formed. " Direct " methods have given way to-day to the so-called " indirect," whereby the malleable end product of greatest use in the arts is the result of a two-step operation; a preliminary smelting producing a relatively crude pig iron, and subsequent refining or conversion of this into steel of the desired composition and properties for various uses.

The most efficient furnace is a shaft type where the fuel and charge to be treated are in direct contact; where these solid materials can be charged at the top and descend by gravity to the base of the stack; where in this descent they may meet a counter current of ascending gases, formed from the combustion of the fuel near the bottom of the shaft; and, finally, where uninterrupted operation is made possible by fusion of all of the products and their withdrawal from the furnace at will in the molten condition. By attainment of suitable temperatures and character of slags, the latter may be easily separated from the iron in the molten condition, due to the different densities and lack of mutual solubility.

577. The Development of the Blast Furnace.—The modern blast furnace, which embodies all of the above characteristics, is the result of evolution and development. The first shaft type furnaces were designed primarily for more efficient and economical operation; the product was malleable material, removed intermittently in the unfused condition. With higher temperatures resulting from increased height of stack and better blast, the spongy mass of iron absorbed carbon from the fuel, and its fusion temperature was lowered from 1500° C. to between 1100° and 1200°. This was below the working temperature of the furnace, and the result was a molten product; but the absorption of carbon up to the limit of saturation of the temperature changed the product from a malleable material to a brittle and relatively weak cast iron, while at the same time there was elimination of slag because of liquation in the fused condition. The era of this development was about 1400 to 1500 A.D. The limited demand for a malleable product, however, practically nullified the advantages of the method until the birth of the puddling process in 1784 gave a refining on a scale commensurate with the capacity of the shaft type of furnace.

578. Description of a Modern Blast Furnace.—In the early part of the eighteenth century, the blast furnace for the manufacture of pig iron was a square masonry stack, with four tuyeres near the base for the introduction of cold blast furnished by a crude blowing equipment. Its dimensions were about 10 ft. across by 30 ft. high, and production was from 30 to 40 tons of pig iron per week with a consumption of 3 tons of fuel per ton of iron. The furnace was usually placed at the side of a hill, so that materials of the charge could be hauled by team to the level of the top.

Important events in the development of the blast furnace have been the substitution of coke for charcoal at the beginning of the eighteenth century, and the invention of the steam engine in the latter part of that century; both of these made possible larger furnaces, more rapid driving and less restriction in location of plant. Hot blast was introduced in the early part of the eighteenth century, and with the resulting increase of temperature of the hearth, there was an increase in furnace production per unit of capacity, with decrease of fuel consumption. Closing of the top of the furnace enabled the top gases to be collected and utilized for blast heating, boiler firing and the like.

Developments in late years have been chiefly of a mechanical nature—enlargements of capacity, the adoption of the circular steel shell with brick lining, evolution of furnace lines as dictated by experience and by the changing character of the available ores; and most especially, in the installation of mechanical handling appliances to eliminate hand labor to the greatest degree, and make for larger output and more economical operation.

The modern blast furnace has a daily capacity from 100 to 1000 tons, 700 tons may be considered fairly standard. Fuel consumption is approximately one ton of coke per ton of iron—it varies from 1700 to 3500 lb. according to character of ore and details of practice. Furnace diameters are from 15 to 25 ft. at the base and the height is from 60 to 100 ft.

A section of a modern blast furnace is given in Fig. 1. It is of the vertical shaft type, of two cone frustums, with their bases together, and resting upon a short cylindrical lower section. The long, gradually outward flaring-portion furnishes the shaft for the descent of the charge for the absorption of heat from the ascending current of gases,

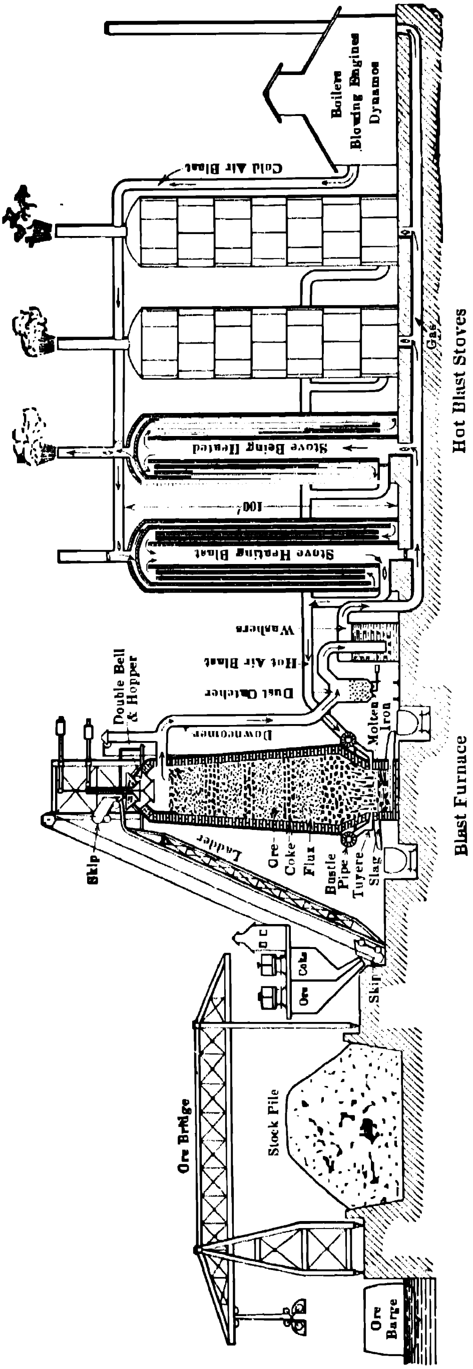


Fig. 1.—Diagrammatic Sketch Showing Scheme of Operating a Blast Furnace.

and for the step by step reduction of the ore to metallic iron. This operation begins shortly below the top, and is practically completed by the time the charge reaches the part of the furnace of greatest diameter. The outward flare is to take care of the increasing volume of material due to any swelling of the charge, and to allow of easy descent without danger of sticking. The lower frustum, called the "bosh" of the furnace, is the hottest part and forms the zone of fusion. There is a rather sharp flare of the walls inwards in the descent in accordance with the diminished volume of material in this zone. Also this bosh angle tends to promote arching, thus supporting the charge column, and to contract the base of the furnace to the diameter needed for the crucible and for penetration of the blast. The lower cylindrical portion is the crucible, or hearth, and serves as a reservoir for collection of the iron and slag between the periodic taps.

The upper shaft of the furnace is of steel-plate construction and sets upon a "mantle ring" in turn supported by 8 to 12 columns. This portion is lined with fire-brick to a thickness of 4 to 5 ft. The bosh zone in general is of brick work from 2 to 3 ft. thick, and without a metal shell. Support is furnished by a series of heavy steel bands, and several rows of "bosh plates" through which water is circulated are set in the brick work to assist it in withstanding the high temperature of the fusion zone. The crucible is surrounded by a heavy jacket of segmental steel castings, and has a fire-brick lining about 3 ft. thick.

The blast is introduced through 8 to 16 tuyeres, or nozzles, made of bronze or copper, and water cooled; these are connected by suitable pipes to the large blast main surrounding the furnace and connected with the stoves and blowing engine. At the lower level of the crucible is the tap hole, from which the pig iron is run into sand beds or large ladles. Just below the tuyeres is a "cinder notch" through which the slag accumulated between taps of iron can be flushed. Near the top of the furnace are one or two openings for the escape of the gases. These gases are led by a pipe to the stoves, boilers, and other points of consumption. The top of the stack is closed by a conical bell and hopper; in the most modern furnaces this is double, to prevent escape of gas which would occur during the lowering of a single bell in charging. Old furnaces were charged by hand buggies taken to the top by an elevator. Modern construction is an inclined bridge up which skips are hauled and automatically dumped after being filled at pits at the base of the furnace.

Typical dimensions of a modern blast furnace of 1000 tons daily capacity are—crucible, diameter 24 ft., bosh, 26 ft., bell, 14 ft., height, 90 ft. Such a furnace would require daily about 3500 tons of charge material—ore 2000 tons, coke 1000 tons, flux 500 tons. This material is charged at the top in alternate layers as required to keep the furnace full. The molten iron is tapped off every five hours and cast into pigs of 150 lb. weight or taken away in ladle cars for conversion into steel. The slag, which may be of greater total weight than the iron, floats on top of the iron, and is flushed off at intervals and usually dumped as waste material either molten or after water granulation. Some of the slag finds outlet in cement making, for road ballast, and for various other uses.

579. Accessories to the Blast Furnace.—The top gases are combustible. They contain carbon monoxide diluted with much carbon dioxide from the reduction of the ore and decomposition of the limestone, and large volumes of nitrogen derived from the air of the blast. This gas is freed from dust to varying degrees by dust catchers, scrubbers and washers, and used in part for heating the blast; the rest is available for power purposes. The air blown into the furnace is preheated to about 500 to 600° C. by four stoves, Fig. 1. For the 1000-ton furnace noted above each stove would be about 20 ft. in diameter and 100 ft. high, consisting of a steel shell lined with fire-brick and containing a combustion chamber and a heat-absorbing chamber of fire-brick checker work. The stoves operate on the regenerative principle—combustion of the gas for one hour results in sufficient heat absorption to enable each stove to heat the entire cold blast for one-half hour. With four stoves per furnace, one heats the air, usually two are on gas and the fourth is held in reserve.

Besides the accessories used in heating and cleaning the blast, power is needed for orehandling and for pumping the enormous quantities of water used for cooling. Also 4500 to 5000 horse-power is required for supplying the 70,000 cu. ft. of air required per minute for a 1000-ton furnace. Blast pressure is about 18 lb. per square inch.

580. The Essential Reactions in Extracting Pig Iron.—The underlying chemical principle in the extraction of iron from its ores is comparatively simple. The ores are oxides in the natural state, or converted to oxides by preliminary roasting or calcination. The problem involves reduction of an oxide (ore) by a reducing agent (C) with the aid of heat (combustion of C). The ideal reaction would be

$$2Fe_2O_3+3C=4Fe+3CO_2,$$

requiring 36 units of carbon to yield 224 units of iron, or a ratio of 6 iron to 1 reducing agent. In addition to the above, there would be needed the heat required for continuance of the above reaction, since that furnished by the combustion of carbon to carbon dioxide is only $\frac{3}{4}$ of the quantity necessary to dissociate the oxygen from the union with the iron. Also if the resultant iron is to be fused, together with the associated gangue of the ore, still more fuel would be required. Actually the conditions in the blast furnace result in variation from the reaction cited above. The ore and coke are charged together at the top of the furnace, and descend slowly through the shaft in contact. No combustion of the fuel takes place until it reaches the air supply at the tuyere zone, where intense heat generation results. The products of combustion pass rapidly up the stack, giving up heat to the charge in their ascent and causing a temperature gradient in the furnace from 1600° C. in the tuyere zone to 200–300° C. at the top of the furnace. The carbon dioxide formed at the tuyeres undergoes almost immediate change to carbon monoxide in the presence of the large coke bed, and as such passes upwards through the stack. As a gas, it has great penetrating power; furthermore it will begin to reduce iron oxide at temperatures as low as those of the blast furnace top, and will practically complete the reaction at temperatures at which solid carbon begins to act. Consequently, although the ore and carbon are in contact, with ores of reasonably porous texture, the reduction may be considered as effected through the agency of the carbon monoxide. The ideal reaction is:

$$Fe_2O_3+3CO=2Fe+3CO_2.$$

Under these conditions there would result 112 units of iron for each 36 units of carbon, or a ratio of 3 to 1. Unfortunately, conditions of chemical equilibrium govern the approach to the ideal which can be obtained, and experience indicates that with the temperatures, pressures and materials prevailing in the blast furnace, the ratio of carbon monoxide to carbon dioxide is usually about 2 to 1. The blast furnace reduction of iron may be typified approximately as follows:

$$Fe_2O_3+9CO+17.1N=2Fe+6CO+3CO_2+17.1N.$$

The result is a production of 112 units of iron with the consumption of 108 units of carbon, or an approximate ratio of 1 to 1. The combustion of the 108 units of carbon to CO in the tuyere zone results in sufficient heat generation to fuse the iron and slag and in the surplus heat needed to complete the reactions in the upper zones of the furnace. Passing from the shaft is a gas which has considerable combustible value because of the high carbon monoxide ratio, but which is diluted by the carbon dioxide and particularly by the large volumes of inert nitrogen accompanying the oxygen in the air blast.

The simple equation of reduction given above is complicated by the successive stages taking place in the zones of descent, by the changes accompanying varying physical conditions in charge and atmosphere, and by the reversibility of reactions and conditions of chemical equilibrium as influenced by mass relations.

In actual blast furnace practice fuel ratios are subject to considerable variation with varying richness of ore and coke and details of furnace construction and operation. From 1600 to 2600 lb. of coke and from 700 to 1200 lb. of limestone per gross ton of pig iron is about the range for modern furnaces working on Lake Superior ores. In 1915 the averages in pounds per gross ton of pig iron for constituents of the charge in the blast furnaces of the United States were as follows:

Coke.	Limestone.	Ore.	Cinder, etc.
2252	1107	4128	334

In Fig. 2 is given a diagrammatic representation of the typical reactions of the blast furnace, together with the weights of the several materials making up the charge and the products. These are based upon a dry ore containing 60 per cent iron, coke containing 87 per cent carbon, pure limestone, pig iron with 4 per cent carbon and 1 per cent silicon, and a tunnel head gas of 1 part CO₂ to 2 parts CO, by volume. Beginning at the upper left corner of the diagram and following the sequence of figures to the right, one observes how the ore, coke and limestone are affected as they gradually move downward in the furnace, also how the gases are transformed as they pass upward through the charge.

581. The Reduction of Impurities in Iron Ores.—Besides reducing iron ore to the metallic state, the blast furnace causes a variable reduction of the constituents of the gangue, flux, or fuel, and an absorption of the liberated metalloids by the iron, to its benefit or detriment. By regulation of temperature and slag characteristics, the blast furnace manager has a considerable degree of control over certain these. Carbon is taken up from the fuel in the fusion zone in fairly fixe amounts of 3½ to 4 per cent. The percentage varies with the amounts of ther elements in the iron; silicon decreases total carbon; manganese i eases it. Whatever phosphorus is present in ore or fuel is readily re ed to the elemental form and absorbed by the iron. It cannot be co olled under the reducing conditions of the blast furnace, and appears i he iron to the full extent which it may be present in the charge. The resence of phosphorus is detrimental in steel-making irons, and in cas rons, except where considerations of fluidity overtop those of strength.

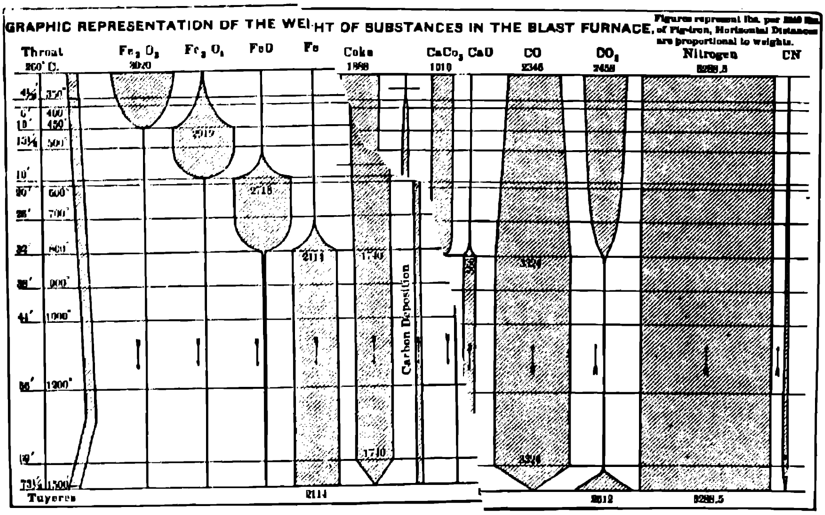

GRAPHIC REPRESENTATION OF THE WEIGHT OF SUBSTANCES IN THE BLAST FURNACE.
Figures represent lbs. per 2240 lbs. of Pig-iron, Horizontal Distances are proportional to weights.
Throat
200° C.
Fe₂O₃
2020
Fe₃O₄
FeO
Fe
Coke
1898
CaCo₃ CaO
1010
CO
2346
CO₂
2458
Nitrogen
8288.5
CN
2019
2718
2011
1740
Carbon Deposition
3324
1740
2114
8012
8288.5
Tuyeres

FIG. 2.—Showing Changes which Occur in a Blast Furnace Charge. (From Campbell's *Manufacture and Properties of Iron and Steel.*)

Manganese is present to varying extent in e ores of iron. Part of it is reduced and appears in the iron, the amou varying with the quantity in the ore and running conditions in the furn e. For ordinary grades of pig iron, control of furnace conditions is no egulated by manganese consideration; the relative amounts in iron and slag are the result of conditions determined by elements more vitally affecting quality.

In ordinary grades of pig iron silicon is desired in fairly fixed percentages, varying from 0.75 to 3.5 per cent according to use. With increasing temperature in the hearth zone, there is increasing tendency for reduction of SiO_2 by carbon; offsetting this is the strong affinity of lime or other bases to unite with SiO_2 to form silicates. Such silicon as is set free in the metallic state is absorbed by the iron; unreduced SiO_2 forms part of the slag. High silicon in the pig iron results from high temperatures of running (usually the accompaniment of higher fuel ratios). Slags of high basicity, that is with the lime or other strongly basic flux held to a maximum, tend to retard the liberation of silicon.

Sulphur is an undesirable element in most iron and steel, in amounts exceeding about 0.10 per cent. And since the amount present in ores of a blast furnace charge may approach 1 per cent, and since the removal of sulphur is best effected under reducing conditions, its elimination by proper control of blast furnace conditions is a most important function of operation. As iron sulphide it is absorbed by the iron; as calcium sulphide it will be dissolved by proper slags; elimination from the pig iron depends largely upon the formation of calcium sulphide. Excess of lime above the amount needed for complete satisfaction of the silica (neutralization of acid by base) together with high temperature, favor the reduction of lime (CaO), in which case the free calcium will take hold of any sulphur to form calcium sulphide, which is soluble to limited extent in the hot, limey slag. Low sulphur pig iron is the result of high temperature furnace operation with high-lime (basic) slags of sufficient quantity to ensure solution of all of the calcium sulphide formed before the saturation limit is reached.

582. Grades of Pig Iron.—Analyses of typical grades of pig iron are given in the following table. It will be noted that the carbon content is not given. Although it is the most important element in cast irons, its percentage is fairly constant—3.5 to 4 per cent—in pig iron, and is largely governed by the amounts of other elements, as noted heretofore.

Foundry irons are intended for the manufacture of iron castings. Softness and soundness are desired with reasonable strength. Increasing the silicon content promotes the formation of graphitic carbon, and thus tends to increase softness. Sulphur promotes formation of combined carbon, and tends to increase hardness. High phosphorus decreases strength but increases fluidity and therefore is of value in the manufacture of thin castings, stove-plate, etc. Foundry pig irons are of higher grade (and value) with increasing silicon and decreasing sulphur content. Gray forge iron is a lower or off grade of foundry pig, often used in puddling.

Malleable Bessemer pig iron is intended for the production of malleable cast iron. Silicon is held within restricted limits to ensure a hard white casting which will be subsequently converted to the proper soft gray texture by annealing. Phosphorus is kept low because of strength considerations, but not too low to destroy fluidity in casting.

	Si.	S.	P.	Mn.
No. 1 Foundry	2–3	<0.035	0.5–1.0	<1.0
No. 2 Foundry	2–2.5	<0.045	0.5–1.0	<1.0
No. 3 Foundry	1.5–2	<0.055	0.5–1.0	<1.0
Gray Forge	<1.5	<0.100	<1.0	<1.0
Malleable Bessemer	0.75–1.5	<0.050	<0.20	<1.0
Bessemer	1–2	<0.05	<0.10	<1.0
Basic	<1	<0.05	<1.0	<1.0
Basic Bessemer	<1	<0.05	2–3	1–2

< = below or less than

Bessemer pig iron has a silicon content sufficiently high for the fuel requirement of the acid Bessemer steel-making process. Phosphorus must be below the limiting amount for a satisfactory steel.

Basic pig irons are intended for steel making by basic processes in which phosphorus can be removed. Economic slag conditions necessitate low silicon. In the basic Bessemer method high phosphorus is needed for its fuel value; it is not essential in the basic open-hearth method.

583. Slags.—Blast-furnace slags will in general have a silica plus alumina ($SiO_2+Al_2O_3$) content about equal to the lime plus magnesia ($CaO+MgO$), and these four constituents will form about 96 per cent of the total slag. Typical analyses will show SiO_2, 25 to 50 per cent; Al_2O_3, 5 to 20 per cent; CaO, 25 to 50 per cent; MgO, 0 to 25 per cent.

584. The Efficiency of the Blast Furnace.—As a utilizer of heat the modern blast furnace is one of our most efficient types of furnace. The heat balance of a furnace of 550 tons daily capacity is tabulated on p. 541.

It will be noted from the heat balance sheet that account is made of the heat energy of the dry top gases due to their temperature only. If account is made of the combustion energy in the carbon monoxide in the top gas—9,000,000 B.t.u.—it appears that 33 per cent of the total available heat energy in the furnace is utilized in reducing impurities in the ore, that 19 per cent is lost through operations of a secondary character and that approximately 48 per cent passes out with the top gases. Of the latter amount about 41 per cent is usable. About 20 per cent of the total heat energy is needed to run the stoves, which having an efficiency of about 50 per cent return 10 per cent to the furnace. Consequently 31 per cent is available for power. With steam boilers and engines, all of this surplus is needed for the hoisting, pumping, and blowing requirements of the furnace. But with large plants and efficient gas engine installation, about 25 per cent of the total energy of the fuel is available for surplus power after plant requirements have been satisfied. This approximates 48,000 theoretical horse-power of surplus power for a furnace of the capacity considered. If the gas were used to drive gas engines about 15,000 horse-power could be developed.

HEAT BALANCE SHEET FOR ONE TON OF PIG IRON

Showing an efficient performance of a 550-ton blast furnace operating under a high temperature (673° C. or 1243° F.) blast

(W. Mathesius, *Bull. Am. Institute Min. Engr.*, Mar., 1915)

HEAT GENERATED.			HEAT CONSUMED.			
By.	B.t.u.	%	By.		B.t.u.	%
Combustion C to CO....	3,995,000	31.1	Reduction of Fe_2O_3 ...	6,133 300		
Combustion C to CO_2....	6,754,000	52.6	Reduction of Fe_3O_4.....	490,000		
Hot blast (heat content)..	2,057,000	16.0	Reduction of MnO.....	48,400		
Moisture of air in hot blast (heat content).........	42,000	0.3	Reduction of P_2O_5......	7 000		
			Reduction of SiO_2.....	418,500		
					7,107,200	55.3
			Calcination of carbonates........		702,000	5.5
			Dissociation of moisture in blast...		397,000	3.1
			Carried off with iron.		1,142,500	8.9
			Carried off with slag...........		909,000	7.1
			Carried off with dry top gases.....		752,400	5.9
			Carried off with moisture in top gas		700,100	5.4
			Radiation, cooling water, and unaccounted for		1,137,800	8.8
Total..............	12,848,000	100.00	Total.....................		12,848,000	100.00

CHAPTER XVIII

MANUFACTURE OF WROUGHT IRON AND STEEL

585. Introduction.—Of the total annual production of iron and steel in the United States, about 80 per cent is steel and the remainder cast iron. Although direct production of the steel from the ore is feasible, and seemingly would be advantageous, in view of the proportionate magnitude of its consumption, economic considerations have determined that present practice should reduce practically all of the ore to the form of crude pig or cast iron, as one step in the manufacturing process; then convert this product into steel by refining or purification as the second step. Typical analyses of crude and finished product are as follows:

	C	Si	S	P	Mn
Pig iron............	3.5–4	1–3	0.03–0.12	0.05–1.0	0.50–1.0
Steel..............	0.10–0.75	0.05–0.20	0.03–0.07	0.03–0.10	0.30–0.75

Service requirements of strength and ductility necessitate the reductions of the amounts of the elements in the pig iron, in particular the carbon, silicon, and at times the phosphorus, to the lower limits prescribed by experience.

586. The Purification of Pig Iron.—Oxidation is the essential chemical principle upon which processes for the conversion of pig iron into steel are based. The accompanying tabulation shows the principal reactions and the quantities of heat thus generated.

Reactions.	Calories of Heat Generated.	
	Per Kg. of Metal.	Per Kg. of Oxygen.
$Si + O_2 = SiO_2$........................	6428	5625
$Mn + O = MnO$........................	1653	5681
$C + O = CO$........................	2430	1823
$Fe + O = FeO$........................	1173	4106
$P_2 + O_5 = P_2O_5$........................	5703	4562

Oxygen will unite with silicon to form SiO_2, and manganese to form MnO, both of which products are insoluble in the molten iron, and because of lower specific gravity, will rise to the top as slag. The silica (SiO_2) will in turn unite with the manganese oxide (MnO), or any other basic constituent, such as iron oxide (FeO) or lime (CaO), to form stable silicates of a more fusible character than the constituent radicles. Carbon will oxidize to carbon monoxide (CO) (or to CO_2 at times) which will bubble through the bath and escape as a gas. The relative order of affinity for oxygen is about as given in the above list of reactions. After the silicon, manganese and carbon have been eliminated, iron will oxidize to FeO, a very small proportion of which is soluble in the molten iron; the greater part, however, rises to the top of the bath and becomes a basic constituent of the slag. Phosphorus will oxidize freely to the gas P_2O_5: but under the conditions prevailing in the steel-making operation, this element will not be eliminated unless it is locked up in the stable form of calcium phosphate $(CaO)_4P_2O_5$. To accomplish this end, lime additions to the bath are necessary, and form the essential feature of the basic process, which will be discussed more fully later.

The oxygen needed in the reactions may be obtained from the air; or it may be gotten by adding Fe_2O_3 to the bath, in which case the oxygen is seized by the silicon, manganese, or carbon, and the liberated iron becomes part of the resultant steel. A significant feature in the tabulation of reactions given above, is the heat liberation accompanying each. All of the elements which it is desired to eliminate from the iron have a fuel value, in most instances greater than that of carbon itself. With proper details of combustion these fuel values may be utilized not only to supply the heat dissipated during the interval of refining a molten bath of cast iron, but in addition to furnish the increment of heat needed to raise the temperature the several hundred degrees necessary to ensure fluidity in the final steel. To illustrate: A ton of coal may be burned so slowly and inefficiently that there will be barely appreciable liberation of heat and a maintenance of temperature hardly sufficient to ensure continuous ignition and combustion. On the other hand, by rapid combustion with forced draft in an efficient type of furnace, heat liberation and temperature is such that iron or other refractory substances may be melted. The total quantity of heat is in both instances the same; temperature rise is the result of rapidity of generation and effectiveness of utilization. If oxidation of the elements in a bath of pig iron is sufficiently rapid, temperature rise may result; if slow, rate of heat generation may not equal that of its dissipation, and fuel from other sources may be required to keep the bath molten.

THE MANUFACTURE OF WROUGHT IRON

587. History.—Modern steel-making methods were preceded by the puddling process, invented by Cort in 1784, improved by Hall in 1830, and persisting to the present day, although it went into the background with the inception of the Bessemer process and the "Age of Steel," in 1856. Puddled iron is to-day about 2 per cent of the annual output of iron and steel.

588. Methods of Manufacture.—The puddling operation is carried out in a reverberatory furnace with rather small hearth and large grate area to ensure the working temperature desired. A longitudinal section of such a furnace is given in Fig. 1.

The furnace has a dish-shaped hearth consisting of a cast-iron bottom plate on which is fused about two to three inches of protecting cinder, essentially oxide of iron. The sides and ends are lined with iron ore. Side doors are provided for handling the charge and product, and for rabbling the bath during the refining operation. The furnace has a low-hanging arched roof of refractory brick. The fuel is usually bituminous coal, preferably of low sulphur percentage and of high volatile content to ensure a long flame. Heating of the bath is accomplished entirely by the temperature of the gases and by their combustion over its surface. The products of combustion escape to a stack, necessarily at high temperature. To save some of the heat, waste heat boilers are often installed above the furnace, and the furnace gases pass through the boiler flues before they enter the stack. Natural draft is used, and there is no preheating of the air used for combustion.

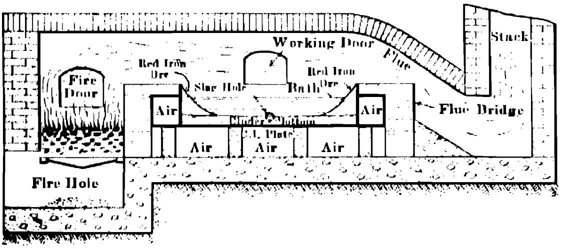


FIG. 1.—Showing Principle of Puddling Furnace.

The capacity of puddling furnaces ranges from 300 to 1500 lb. per heat; in general about 600 lb. Pig iron of white or mottled grade, and known as forge or mill iron, is charged on the banks of the hearth, together with some old slag or iron oxide to furnish a slag blanket for the bath, and to serve as the basic constituent of the new slag and as oxidizing agent in the refining.

A single heat takes about one and a half hours. After melting of the charge, iron oxide additions are rabbled into the bath and serve to remove practically all of the silicon and manganese and some of the phosphorus into the highly basic iron silicate slag, thus formed. Carbon is next oxidized to carbon monoxide, and in bubbling through the bath causes much boiling and agitation. These operations take up somewhat over two-thirds of the time of the heat. With elimination of carbon and close approach to purity, the fusion point of the charge becomes raised from about 1200° C. to 1500° C. The furnace temperature, high enough to melt down the pig iron and keep the charge molten during the greater part of the time of refining, is not sufficiently high to fuse the refined product, and it solidifies to a pasty mass, which can be worked into balls of a weight of a couple of hundred pounds. These balls are removed from the furnace dripping with slag, which is fluid at the finishing temperature. This fluid slag is largely removed by an eccentric roller squeezer, and the bloom thus formed is rolled into flat "muck bars" about $\frac{3}{4}$ by 3 in. to 6 in. in cross-section.

The results of the conversion operation are as follows:

	C	Si	S	P	Mn
Pig iron.	3.5 –4.25	1–2	0.03–0.10	0.50–1.00	0.25–1.00
Wrought iron.	0.02–0.10	0.10–0.20	0.01–0.06	0.05–0.20	Tr.–0.10

Considerable of the silicon, phosphorus and manganese in the wrought iron is associated with the 2 to 3 per cent of occluded slag which is not removed in the squeezer. The slag contains 60 to 80 per cent of the oxides of iron, 15 to 30 per cent of silica, together with the oxides of manganese and phosphorus.

Further density and homogeneity is imparted to the iron by hot rolling of the muck bars. Thus *refined bar iron* is made by cutting muck bars into equal lengths, stacking them parallel in rectangular piles, binding with wire, and rolling to size. Scrap bars of wrought iron of length equal to the muck bars may also be included within the pile but no steel is permitted. *Double-refined iron* is made entirely of muck bars which are twice piled and rerolled with all bars in the final pile of length equal to the pile. In plates and sheets the ductility and strength in the transverse and longitudinal directions can be made more uniform by rolling in both directions. The methods of rolling wrought-iron shapes are similar to those given in Ch. XIX.

Aston's Process for making wrought iron, put into operation at the A. M. Byers Co. plant in 1930, is a less expensive method of producing high-grade wrought iron than the puddling process. In this process pig iron is continuously melted in cupolas and tapped into ladles, where it is desulphurized. It is then purified in a Bessemer converter and poured at a controlled rate into a ladle containing an iron silicate slag. The slag is made in an open-hearth furnace from iron oxide and silicious materials.

Owing to the lower temperature of the slag, the iron is rapidly solidified into pasty particles and also freed of gases. The particles agglomerate in the bottom of the ladle into a 3- or 4-ton sponge ball impregnated with slag. The sponge ball is then squeezed in a press which ejects the excess slag and welds the ball into a bloom. Subsequently, the bloom is rolled into desired shapes.

589. Kinds of Wrought Iron and Their Uses.—Pure wrought iron, as above described, on account of its good welding properties and resistance to corrosion is in considerable demand for blacksmith stock, welded pipe, roofing sheets, crane chain, staybolt iron, and as a base for high-grade tool steels.

In addition to the above-mentioned types of pure wrought iron, the following three varieties of the product may or may not contain additions of steel scrap: *fagoted iron*, *busheled iron*, and *charcoal iron*.

Fagoted iron is hot rolled from box piles the outsides of which are formed from muck bars or soft steel plates and the interior of scrap wrought iron or soft steel. If the stock is all wrought iron a homogeneous product of good quality may result, but if there is much scrap steel in the box piles the iron is likely to be of poor quality. This product is often made into merchant bars and plates.

Busheled iron is made in much the same way as muck-bar iron excepting that the metal charged is wrought-iron scrap, steel scrap or a mixture of both. On account of the variability in the composition of the scrap it is not as homogeneous as puddled iron. Busheled iron is considerably used in making *common iron* plates and sheets where forging and welding properties are of minor importance.

Charcoal iron is made either from charcoal pig iron or from wrought-iron and steel scrap. Charcoal pig iron is made by remelting ordinary pig iron in a hearth heated by charcoal. It is much used in Sweden for the production of the famous high-grade wrought iron of that country. In America most of the charcoal iron is made by remelting wrought-iron and steel scrap in contact with a charcoal fire. This is generally done in a knobbling or sinking fire where the metal is charged on the bottom of the hearth and the charcoal fuel placed above it. During smelting the furnace-man continually lifts the metal to permit oxidation of impurities by a strong air blast. The latter is admitted through a tuyere placed on the side of the hearth. Knobbled charcoal iron is freer from slag and more ductile than ordinary puddled iron. It is surpassed, however, in both respects by Swedish charcoal iron. Knobbled charcoal iron is used in making crucible steel and is a good material for stay-bolts, engine-bolts and other forms requiring a tough, ductile metal with high resistance to corrosion. It also possesses excellent forging and welding properties.

STEEL MAKING

590. Classes of Processes.—The prominent present-day steel-making processes are as follows:

Bessemer or Pneumatic	acid basic or Thomas-Gilchrist.
Open-hearth or Siemens-Martin	acid. basic.

The distinctive difference between Bessemer and open-hearth processes is essentially one of type of apparatus to effect the conversion; while the acid and basic methods, adaptable to either type of equipment, differ in the chemical reactions involved, and in the resultant character of refining and elimination which may be effected.

The fundamental difference of acid and basic processes is the type of slag; in the former, slags of acid character, that is, high in SiO_2, or with the silica unsatisfied, are formed. And since any unsatisfied silica in the slag would tend to reach saturation by attacking any bases with which it might come into contact at high temperature, the refractory lining of the furnace is made of acid material (silica, gannister, mica schist, etc.) to prevent scouring. With acid slags there is no absorption and holding of phosphorus which might tend to be oxidized during refining. The acid process will not eliminate phosphorus.

The basic process provides basic slags, usually by lime additions in sufficient quantity to more than satisfy the silica and to have the basic constituents predominate. This can only be ensured by lining the furnace with basic refractories (magnesite, dolomite, etc.) since any excess base would tend to neutralize itself by scouring an acid lining with which it might come in contact at high temperature. With excess of lime in the slag, phosphorus after oxidation to P_2O_5, unites with such lime to form the stable phosphate $(CaO)_4P_2O_5$, which in turn is absorbed by the slag. The basic process will eliminate phosphorus; likewise by proper conditions of working, there is a slight oxidation of sulphur, and some further elimination as calcium sulphide.

THE BESSEMER PROCESS

591. Principle of the Process.—The Bessemer process was introduced in 1856. It depends upon the essential principle of sufficiently rapid oxidation of the elements—Si, Mn, and C—which it is desired to remove from the iron, to keep an initially molten bath fluid throughout the whole of the refining operation, and deliver a molten product. In such case, because of lack of mutual solubility and differences of specific gravity, the slag separates from the steel by flotation, and the latter (unlike wrought iron) is free from this constituent.

592. The Converter.—A cross-section of the Bessemer vessel is shown in Fig. 2. It consists of a steel shell in three detachable sections—bottom, body, and nose. The body section is cylindrical, while the nose tapers to a relatively small opening, in order to conserve heat, prevent excessive ejection of metal and slag, and to provide for proper handling of metal in charging and pouring. The nose section may be concentric with the body axis, or set eccentrically. The several sections are held together by means of stirrups and wedges, in order that they may be readily separated in spite of heat and slag accumulations. The shell is supported on trunnions, one of which is hollow to allow of the blast being kept on regardless of the position of the converter. A pipe leads from the hollow trunnion to the wind box at the bottom of the vessel. The converter is tilted by means of a pinion mounted on the trunnion, and rotated by a hydraulically operated rack.

Bessemer vessels are built in sizes from $\frac{1}{2}$ ton to 25 tons capacity per heat; in general 10 to 25 tons represents the customary steel works size. In acid working, the body and nose are lined with a 12-in. thickness of rammed ganister, or blocks of mica schist or other silicous material. The bottom section is a pan, with rammed silica lining about 2 ft. thick. In this bottom are set 15 or 20 silica refractory tuyeres, each provided with a dozen or more holes from $\frac{1}{2}$ to $\frac{5}{8}$ in. in diameter. A clay joint is made in keying the bottom to the body, to prevent leakage of metal. The body lining lasts for 10,000 to 20,000 heats, or a period of several months. The bottom is worn away in 20 to 25 blows, or a period of five or six hours. This is due to the fluxing action of the iron oxide formed at the bottom immediately upon entrance of air through the tuyeres. Facilities are provided for rapid change of bottoms.

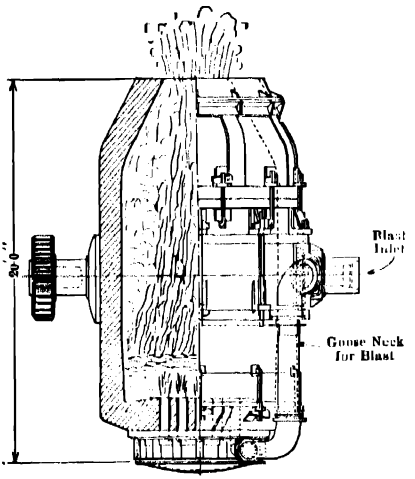


FIG. 2.—A 15-ton Converter.

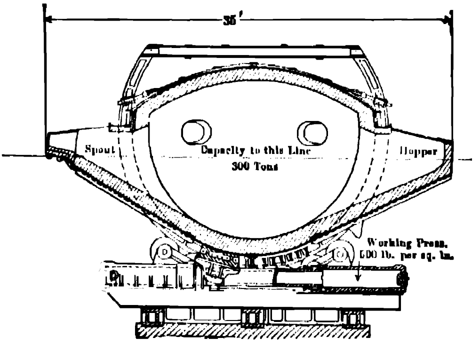

35'
Spout
Capacity to this Line 300 Tons
Hopper
Working Press. 600 lb. per sq. in.

FIG. 3.—A 300-ton Mixer.

593. The Acid Bessemer Process.—The charge for the converter must be molten. The pig iron may be melted in cupolas, but is now usually brought in ladle cars from large mixers or reservoirs of 200 to 600 tons capacity (Fig. 3), the mixer in turn taking its hot metal from the blast furnace. In this way there is no confusion or delay in working because of the large casts of the blast furnace at six-hour intervals, and the relatively small charge requirements of the converter at fifteen-minute intervals. Also, irregularities of composition of the different blast-furnace casts are equalized for the Bessemer heats. In charging, the converter is tilted to a horizontal position, and the hot metal charge poured in; the blast is then put on, the vessel turned upright, and the heat blown. The blast pressure is about 20 to 25 lb. per square inch in bottom blowing and the metal is kept out of the small tuyere openings by this pressure.

The time of blowing is about twelve minutes; for the first few minutes silicon and manganese are chiefly oxidized, and form slag. During this interval there are iron sparks and slag ejections, but no real flame. Then carbon begins to oxidize in the converter to carbon monoxide, and burns at the nose of the vessel to carbon dioxide with a flame which increases in intensity, and is accompanied by the roaring boil of the bath as the gases go through it and agitate it. After several minutes, the flame flickers and drops, a sign to the blower that the carbon is practically burnt out of the bath. With the drop of the flame, the converter is turned down, the blast is cut off, and the metal is cast after the proper additions have been made.

In American practice, the blow is continued until practically all of the silicon, manganese and carbon of the bath have been eliminated. During the interval, iron oxide is formed, and in the absence of the above elements, there is no chance for its reduction to metallic iron at the end of the blow, and a small proportion remains dissolved in the iron of the bath. Also there is saturation of the bath in dissolved gases. A heat poured in this condition would result in rotten steel unsuitable for rolling or forging. The remedy is deoxidation with ferrosilicon and manganese alloy (ferro-manganese or spiegeleisen) added while teeming the steel into the pouring ladle. The silicon and manganese rob the iron of its oxygen, and separate as oxides (insoluble in the bath of steel) into the slag. The manganese, also, if in sufficient quantity, unites with sulphur to form manganese sulphide (MnS), which remains in the ingot but in a form less conducive to red shortness than that resulting from iron sulphide. Final " killing " or quieting of the heat is effected by treatment with small amounts of aluminum thrown into the ingot mold during casting. The manganese alloys, which carry several per cent of carbon, serve also as recarburizers to bring the carbon content of the steel to the amount required by the specifications for varying character of service. The extent of conversion is about as follows:

	C	Si	S	P	Mn
Pig iron	3.5 –4	1–1.25	0.05	0.09	0.50–1.75
Steel	0.10–0.60	0.05–0.20	0.05	0.10	0.30–0.50

The silicon and manganese values in the steel are the amounts of these elements remaining alloyed with the iron, in excess of the requirements for deoxidation. Carbon is added to the limits of specifications; sulphur and phosphorus are not removed during conversion, and are in the steel in greater amount than in the pig-iron charge, because of concentration due to the conversion loss during blowing.

The carbon in the pig iron is in fairly constant amount as it comes from the blast furnace; while the manganese content is largely a characteristic of the iron ore used. Silicon, being the essential fuel in converting, is held to close limits; below 1 per cent there is liability of cold heats, while with rapid and efficient blowing a silicon content much in excess of this amount only tends to prolong the heat and introduce difficulties through too high temperature during the blow.

During the heat there is a conversion loss of 8 to 10 per cent; 5 to 6 being accounted for by the silicon, manganese, and carbon removed; the remainder consists of a loss of iron, some because of sparks and splashing, but principally as iron oxide taken up by the slag to supply its deficiency in basic constituents. The amount thus required varies with the quantity of metalloids removed from the bath, with the composition of the slag, and with the amount of scouring of the bottom. No slag-forming constituents are added during the heat. The quantity of slag formed is about 150 lb. per ton of steel made, and has a composition approximately SiO_2, 50–70 per cent, FeO, 10–25 per cent, MnO, 10–30 per cent.

594. The Basic Bessemer Process.—The basic process was adapted to Bessemer working in 1876 by Sydney Thomas and Thomas Gilchrist. In basic Bessemer practice the vessel is the same as that used for acid working except for the lining of dolomite or magnesite to resist scouring by the basic slag. This lining is rammed into place with a tar binder. Phosphorus removal is effected during the blow by oxidation to the pentoxide (P_2O_5) and subsequent formation of calcium phosphate $(CaO)_4P_2O_5$, which becomes a constituent of the slag. The necessary lime is added to the converter before and during the heat. Silicon, manganese, carbon and phosphorus are eliminated in about the order named and the period of blow is from fifteen to twenty minutes.

Typical conversion is as follows:

	C	Si	S	P	Mn
Pig iron	3.5 –4	0.5–1.0	0.05	2–3	1–1.5
Steel	0.10–0.60	0.20	0.04	0.05–0.10	0.30–0.50

The necessary heat is obtained during the blow from the oxidation of the silicon, manganese, carbon, and phosphorus. The silicon, however, must be kept low, because of its acidity and the increased lime needed to flux it. The deficiency in heat value thus resulting, together with the extra amount required to bring the high lime additions to slag fusion temperatures and to supply the increased radiation losses during a longer period of blow, are supplied by the phosphorus. The suitable pig iron is therefore one having a phosphorus content of 2 to 3 per cent, and is obtained from the ores of special districts, notably in Germany. Basic Bessemer working is not practical in the United States, although many of our Southern ores are suitable. The conversion losses are from 12 to 17 per cent, about 9 or 10 per cent of which is accounted for by the metalloids eliminated. The slag weight will be 400 to 500 pounds per ton of steel, with a composition of SiO_2, 5–15; P_2O_5, 15–20; CaO, 40–45; MgO, 0–10; FeO, 5–20; MnO, 5 per cent. Because of their high content in phosphoric acid, basic Bessemer slags have value as a fertilizer after pulverizing.

595. The Tropenas Converter.—A modification of the standard bottom-blown converter used in steel works is the side-blown vessel of which the Tropenas converter is a type. The air is introduced through the side of the vessel at the surface of the bath under a pressure of 3 to 5 lb. These converters have a capacity of ½ to 2 tons per heat, and are used chiefly for the manufacture of steel castings, where hot steel free from occluded gases is particularly desirable. The lessened agitation of the bath in side blowing favors the latter, although accompanied by increased conversion loss and time of blowing. By allowing part of the tuyeres to deliver free air above the surface of the bath, the initial carbon monoxide is burned to carbon dioxide, and the full calorific value of each unit of carbon (C to CO_2 gives 97,200 calories against 29,160 produced in burning C to CO) is utilized within the body of the converter and the temperature of the bath raised thereby. The molten metal is obtained from cupolas, and must have a silicon content of 2 per cent or upwards in order that sufficient heat may be generated in the small vessel to maintain fluidity.

THE OPEN-HEARTH PROCESSES

596. Essential Features and the Development of the Processes.—The fundamental distinction of the open-hearth process as compared with the Bessemer is the relatively slow rate of oxidation of the impurities; so slow that the heat of reaction is insufficient to keep the bath fluid during conversion, and additional heat from outside sources becomes necessary to insure completion of refining and final fluidity of the steel and slag. Of necessity any coal or coke used as fuel must be in a compartment of the furnace separate from that of the bath, to enable desired oxidation reactions to be carried out. Combustion of coal in a separate grate box will hardly give the high temperature required for fusion of the finished steel, as was noted in discussion of the puddling furnace. The inception of the open-hearth process was marked by the invention of the gas producer by Sir William Siemens in 1862, the utilization of the gas to obtain high temperatures by preheating of the gas and air required for combustion by regeneration, and the development of these principles and their application to the furnace and methods for refining of the steel between the years 1862 and 1868. Siemens method was the use of all pig-iron charges, with iron ore as the agent to supply the necessary oxygen. About the same time the application by Pierre Martin of the Siemens furnace to the manufacture of steel by dilution of pig iron with scrap, and subsequent refining, caused his name to become identified with the development of the open-hearth process; it is still known in Europe as the Siemens-Martin process.

597. The Open-hearth Furnace.—The modern open-hearth furnace is built in capacities of 5 to 100 tons per charge and may be stationary or tilting, the former being the more usual. The smaller sizes are used mainly for the manufacture of steel castings, with usual capacities of 15 to 25 tons. The furnace hearth consists of a shallow steel pan, supported by foundation arches, and lined to a thickness of about 2 ft., with brickwork over which are successive layers of refractory sintered into a continuous bottom. For acid practice, this bottom is made of silica brick and sand; for basic working, of magnesite brick and crushed magnesite or dolomite with tar binder. Fig. 4 shows a longitudinal vertical section of a stationary open-hearth furnace. Fig. 5 shows a transverse section through an open-hearth furnace house.

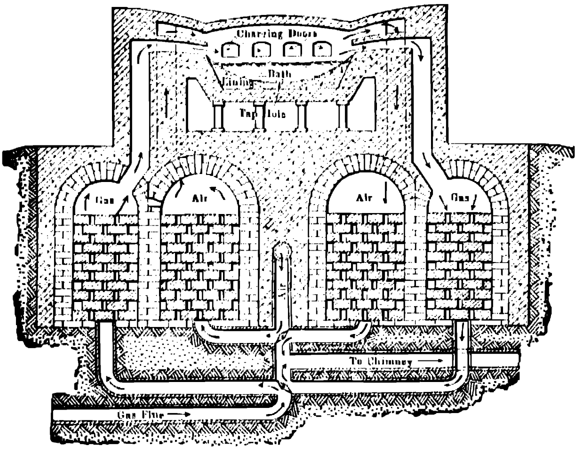


FIG. 4.—Vertical Section through a Stationary Open-hearth Furnace Showing Principle of Operation.
(The regenerators for gas and air are below and behind the hearth.)

A 60-ton furnace has hearth dimensions of about 40 ft. in length by 15 ft. wide, with a depth of metal of 18 to 24 in. Length is limited largely by necessity of high and uniform temperature throughout the bath; width by necessity of effective patching of bottom; while too great a depth means inefficient treating of a charge which must be heated entirely from the top surface.

The furnace is enclosed on sides and top by walls and a low hanging arched roof of silica brick, secured by buckstays and tie rods. Above the hearth there is no contact with slag; therefore there is no necessity for using the more expensive and mechanically weaker magnesite bricks, even in basic practice. Charging is done through doors at one side of the furnace, while in the middle of the opposite side the bottom slopes to a tapping hole. The level of bath and charging floor is usually at sufficient height above the pouring floor to enable ladles to be set under the tapping spout without necessity of deep ladle pits. This arrangement also enables flues, valves, and regenerators to be placed in accessible positions under the charging platform.

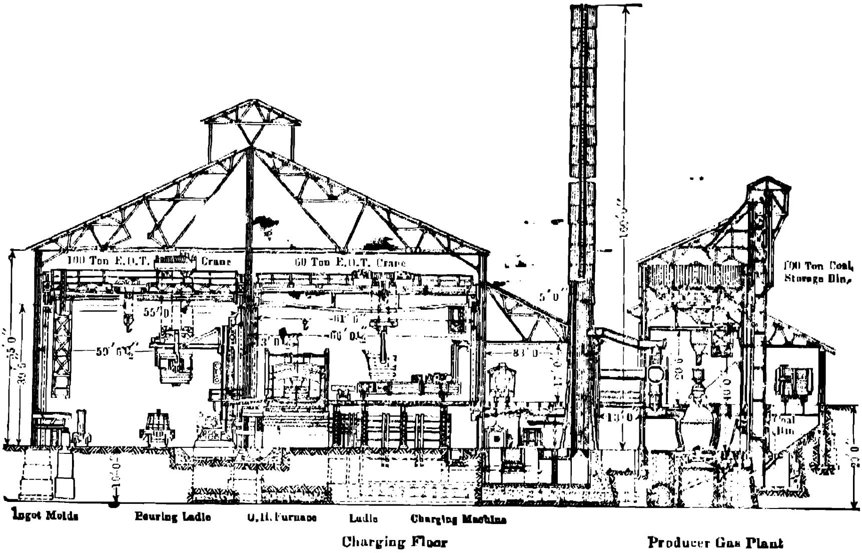


FIG. 5.—Transverse Section of an Open-hearth Plant at South Works of the Illinois Steel Co., Chicago.

At each end of the furnace are separate uptake flues for the gas and air used for combustion, and ports to direct them into the furnace for proper mixture and combustion. The uptake flues lead into heat storing or "regenerator" chambers one each for gas and air at each end of the furnace. These chambers are usually built under the charging floor, and are filled with built-up rows of a checker work of silica brick, so piled as to allow of fairly free passage of the gases, and yet present a large surface of contact for heat absorption and extraction. Between the regenerator chamber and the single stack for each furnace is a set of flues and hydraulically operated valves by which the combustion gases and waste gases can be led to and from either end of the furnace, and reversed periodically as desired. Natural draft is employed.

Producer gas is the customary fuel, although natural gas has played a very important part in American practice, and crude oil, pulverized coal and tar have been used. For other fuels than producer gas only the air required for combustion is preheated, and no regenerators are required for the fuel. In the use of producer gas, both gas and air are heated prior to combustion. The fuel and air ignite at the ports at one end of the furnace, and burn in their passage over the surface of the bath of metal, escaping at the other end at high temperature, approximately that of the furnace itself. Passing on their way to the stack through the regenerator chambers at that end of the furnace, these hot gases give up a large part of their heat to the brick checkerwork. This brickwork stores up a large quantity of heat and in an interval of about twenty minutes has attained a high temperature. The direction of flow of gases is now reversed, and combustion is at the opposite end of the furnace hearth. The entering gas and air, passing through the hot regenerator chambers, absorb their stored up heat, and reach the ports at a temperature of 1000° C. The temperature attained in the furnace is now greater than that due to direct combustion of the fuel and air, by an increment dependent upon the heat stored up in these gases. The waste gases in turn give up their heat to the cooler regenerators at the opposite side of the furnace. The periodic reversals at intervals of fifteen to twenty minutes enable the necessary temperature to be maintained.

598. Conversion by the Open-hearth Furnace.—Usual open-hearth practice is with basic bottoms; in the United States the relatively small tonnage of acid steel is used largely in castings.

The charge may be cold or molten; in the latter case there is some saving of fuel and time. Also since the success of the process does not depend upon the fuel value of the elements in the burden, the latter may vary widely in composition. Usually the charge is a mixture of pig iron and steel scrap; increase of the last named effects partial refining of the bath by dilution.

The reactions are virtually the same as in Bessemer working; an oxidation of the silicon, manganese, and carbon; and in basic practice, an elimination of phosphorus by oxidation and union with lime. The rate of reaction is, however, very slow, and heats require from six to twelve hours, usually about ten hours for basic heats of 80 to 100 tons each. The oxidizing agent is iron ore; by interaction the oxygen of the ferric oxide (Fe_2O_3) unites with the metalloids and is eliminated as gas or slag; the liberated iron in turn becomes a part of the bath. With ore additions it is possible, therefore, to practically offset the conversion loss due to elimination of metalloids, and to keep it to 5 per cent or less. Basic open-hearth slags in this country rarely carry sufficient phosphoric acid to warrant their use as fertilizer; this is due to the moderate phosphorus content (0.20 to 1 per cent) in the charge. Control of the heat is by fracture tests of samples and by chemical analyses of same; the heat is tapped under controllable conditions. Ferromanganese and ferrosilicon additions are made to the ladle on tapping, and aluminum is thrown into the ingot mold as in Bessemer practice.

After each heat the furnace bottom is patched by shoveling in crushed and calcined dolomite, which frits into place at the working temperature. The lining and bottom are good for three to six months of service, when shut down for repairs and rebuilding is necessary.

599. Comparisons of Bessemer and Open-hearth Processes.—Factors of advantage and disadvantage in the Bessemer and open-hearth processes are as follows:

BESSEMER	OPEN-HEARTH
Rapid conversion—10 to 20 minutes.	Relatively slow conversion—6 to 12 hr.
Relatively small heats—1 to 20 tons.	Relatively large heats—25 to 100 tons.
Small plant cost per unit of output.	Heavy plant cost per unit of output.
All fuel is in charge.	Extra fuel—50 lb. of coal per ton hour.
Oxygen obtained from blown air.	Oxygen obtained from iron oxide
Charge must be molten.	Charge may or may not be molten.
Little liberty in composition of charge.	Much liberty in composition of charge.
Control entirely in skill of operator.	Accurate control of product.
Heavy conversion loss—10 to 15 per cent.	Small conversion loss—0 to 5 per cent.
Simplicity of operation.	Operation more complex than Bessemer.

In the United States, steel-making practice is divided almost entirely between the acid Bessemer and basic open-hearth methods. Comparative outputs in the United States, Germany and Great Britain in recent years are given in Table 1:

TABLE 1.—TONNAGE OF STEEL INGOTS AND CASTINGS PRODUCED FROM VARIOUS PROCESSES IN LEADING COUNTRIES

(In Long Tons)

Process.	1913			1937		
	United States.	Germany (Metric Tons).	Great Britain.	United States.	Germany (Metric Tons) Ingots Only.	Great Britain.
Acid Bessemer	9,545,706	155,138	1,048,772	3,449,927	....	233,000
Basic Bessemer	....	10,629,697	551,929	....	7,958,000	
Acid open-hearth	1,255,305	380,155	3,811,382	499,793	229,000	2,260,000
Basic open-hearth	20,344,626	7,592,901	2,251,793	45,772,510	10,811,000	9,677,000
Crucible	121,226	....	....	846,471*	668,000*	452,000*
Other	34,011*	....	....			
Total	31,300,874	....	....	51,792,301	19,818,000	12,963,000

* Principally from electric furnaces.

600. The Decline of the Bessemer Process.—In spite of the simplicity of the Bessemer process and its many other features of seeming advantage over the open-hearth method, the former has been steadily forced into the secondary position in this country. This is largely due to the gradual increase in the phosphorus content of available ores; the difficulty of securing ores of Bessemer grade has caused a spread of price between this and grades suited for basic working sufficient to make the open-hearth method economically attractive. In addition there is the advantage of greater yield in conversion, and the better reputation for quality which open-hearth steel holds in the opinion of users. Bessemer steel finds its principal outlet in steel rails, pipes and tubes, wire and wire rods, plates and sheets, and merchant and agricultural machinery shapes. Practically all structural steel has for years been of open-hearth grade, and in recent years the latter has been rapidly superseding the Bessemer process in the manufacture of steel for rails.

601. The Duplex Process.—The dearth of steel scrap required in open hearth operation, the possibility of conserving existing Bessemer plants and of combining the advantages of converter operation with the elimination of phosphorus are reasons which have led to the successful use of the duplex method at several plants. A heat is blown to virtual elimination of silicon and manganese, and partial removal of carbon. It is then transferred to a basic open-hearth furnace, where the phosphorus is eliminated and the heat slowly finished to the desired quality. In certain plants electric furnaces are being used for the finishing operations in the duplex combination with the Bessemer converter. The duplex method effects a marked saving in the time necessary for treatment in the open-hearth furnace.

MINOR PROCESSES USED IN MAKING STEEL

602. The Cementation Process was the only known method of making steel until A.D. 1500. The process is still used in England for making cutlery and tools but has never found favor in America. The well-established fact that wrought iron packed in charcoal and heated to a bright red will absorb carbon and form a solid solution with it is the basic principle of the process.

For this process the cementing furnace is provided with a pair of long rectangular converting pots made of fire-brick and externally heated by a central fire-box. Long thin bars of the very best quality of Swedish charcoal wrought iron are packed in fine charcoal within the converting pots. The top of the pot is covered with a mixture of grindstone dust, the fire is started, and the temperature gradually raised until it reaches approximately 1000° C. A uniform heat is then maintained for a week or ten days, depending upon the amount of carbon desired in the steel. The carbon content is determined from time to time by withdrawing sample bars and testing them. After the proper carbon content has been secured the furnace is gradually cooled down in another week and the metal is withdrawn.

Since carbon monoxide is evolved during the process the surfaces of the bars are covered with blisters due to the combination of the carbon with the iron oxide in the slag of the wrought iron. Furthermore the impregnation of carbon varies with the distance from the surface of the steel. In order to render the blister steel more homogeneous the bars are sheared into short lengths, piled, heated to a welding heat and rolled down into small bars called single-shear steel. Sometimes the single-shear bars are treated like the blister-steel bars and thus made into double-shear steel.

603. The Crucible Process was invented in A.D. 1740 by Daniel Huntsman of Sheffield, England. The process consists in melting wrought iron together with charcoal and a little ferromanganese in a small barrel-shaped vessel called a crucible. In America, steel scrap occasionally forms a portion of the charge and ferrosilicon is added just before drawing the crucibles. For very superior grades of steel Sheffield makers charge cementation steel instead of wrought iron. Various alloy steels are also made by this process. Thus ferrochromium and ferrotungsten are added to the charge in making chrome and tungsten steels, respectively.

Since neither sulphur nor phosphorus are removed in the process only very pure stock can be used. Crucibles are made of clay, or graphite and clay, and usually hold from 50 to 100 lb. Most of the melting furnaces are gas fired and are built upon the regenerative principle like the open-hearth furnace (Art. 597). Each furnace is provided with two to twenty separate melting holes. In many of the English furnaces coke fires are built in the melting holes in direct contact with the crucibles.

In American practice four to six crucibles are charged with stock, fitted with tight covers, placed in a melting hole, and gradually heated to the melting point in two to three hours. Formerly crucibles were held in the furnace ("killed") for a half hour or more to allow the gases to boil out of the metal, present practice favors the introduction of ferrosilicon and ferromanganese at this juncture which in four or five minutes deoxidize and quiet the metal, thus avoiding a "killing" period. The crucibles are withdrawn as soon as the metal has become quiet (evolves no more gas), the slag is skimmed off and the metal poured into small cast-iron ingot molds or into special forms for steel castings. Ingots are rolled, forged or pressed, as in other steel-making processes, to densify the metal and improve its mechanical properties.

On account of the high cost of labor, fuel, and crucibles, in proportion to the quantity of steel produced, crucible steel is much more expensive than Bessemer or open-hearth steels. Consequently its use is limited to articles of small weight or to special parts where a high-grade product regardless of cost must be used. The crucible process has been largely superseded by the electric furnace process; although it is still used in making tools, cutlery, springs and fine grades of castings. In 1937 this country produced 934 tons of crucible steel.

604. The Electrical Furnace in Steel Making.—Within the last decade rapid strides have been made in the use of the electric furnace both in super-refining steel and in purifying cast iron. In 1937 there were over 500 electric furnaces in the United States and the production of electric steel was in the vicinity of 1,000,000 tons. The electric furnace is somewhat similar to a small open-hearth furnace with electricity instead of gas as a source of heat. The principal advantages of the electric furnace process are: (1) the possibility of securing any desired temperature thus providing a means of removing impurities and occluded gases without perturbation of the bath; (2) the opportunity for changing slags thus rendering possible the removal of various impurities; and (3) high temperature with controllable atmosphere (oxidizing or reducing) as desired.

Because of the great expense in utilizing electricity as a source of heat energy, the electric furnace cannot be efficiently used to purify pig iron unless electrical energy can be purchased at very low rates. In steel making, the electric furnace is principally used to reduce the oxygen, phosphorus and sulphur from steel which has been partially purified by the acid Bessemer process. Superior grades of steel for axles, castings and wire can be made in this way. It is also used to super-refine steel from the basic open-hearth furnace and thus make a high-grade steel which compares very favorably with the best crucible steel in quality, and costs less.

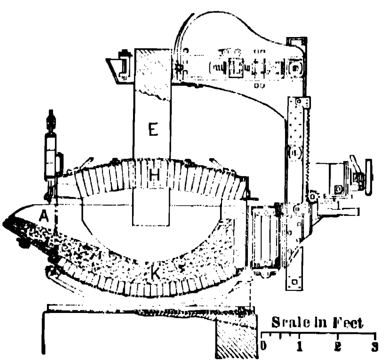


FIG. 6.—Transverse Section of Héroult Electric Furnace.

A, spout; *E*, electrode; *H*, roof; *K*, hearth lining.

The three types of electric furnaces used in refining steel are (1) the radiation arc type in which the current arcs directly from the positive to the negative electrode, both being suspended above the bath; (2) the arc resistance type in which the current arcs from positive electrode to bath and arcs or is conducted from the bath to negative electrodes; and (3) the induction type in which the bath of metal forms the closed secondary circuit in a step-down transformer. Three-phase alternating current is generally used in these furnaces. A Héroult furnace of Type No. 2 has been built with a capacity of 100 tons per charge. On account of its efficiency and adaptability the Héroult furnace is used more than any other electric furnace for refining steel. Fig. 6 shows one of the small single-phase Héroult furnaces. In the larger furnaces three-phase current is used and the three electrodes are set over the bath on the apices of an equilateral triangle. In refining hot metal the larger Héroult furnaces consume from 150 to 200 kilowatt hours per ton of poured metal and require about 1 to 1½ hours for purification. With cold metal the time required is three to four times as long and energy consumption is from four to six times as great.

CHAPTER XIX

THE MANUFACTURE OF IRON AND STEEL SHAPES

605. Essentials in the Production of Shapes.—Iron and steel finds outlet in engineering construction in shapes produced either by casting or some form of mechanical working. In the former operation, the metal is melted and poured into molds made in sand or other suitable refractory substance; fluidity of metal is necessary, and it may be cast iron, steel, or malleable cast iron. Mechanical working of the metal, however, results in improved physical quality, and where this is essential, the required shape is produced by forging or rolling. For the latter operations malleability, at least while hot, is essential, and consequently cast iron is not suitable. Intricate or special shapes are produced by direct forging; or where numerous pieces of the same form are required, by drop forging with dies. By far the greatest tonnage of shapes required in engineering construction is of certain standard sections, uniform in cross-section throughout a length which is, in general, relatively much greater than the cross-section. Rolling mills can produce such shapes in quantity at a speed much greater and a cost much lower than any method of forging or casting.

606. Ingots.—Steel intended for rolling or forging is cast into ingots. These vary in shape and size, but in rolling mill practice are usually square or rectangular in cross-section, 12 by 12 in. to 20 by 20 in. or 18 by 24 in., and from 5 to 8 ft. long. The mold is of cast iron, 3 to 5 in. thick, with open top and bottom. The ingot mold is set upon end on an iron bottom plate, either stationary upon the casting floor, or on cars to enable prompt removal of the ingots after pouring. The mold has a gradual taper in cross-section from bottom tc top, to facilitate freeing of the ingot. Steel is poured into the open top of the ingot mold from a large ladle, Fig. 1, with nozzle and stopper at the bottom, and handled by a crane. When the steel has solidified sufficiently, the mold is stripped from the ingot by lifting the former;

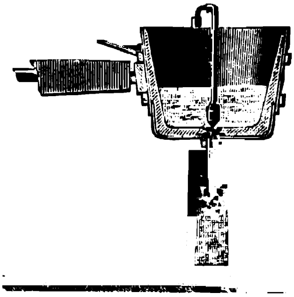


FIG. 1.—The Valvular Ladle.

or in case of sticking, by forcing downwards upon the ingot with a plunger at the same time that the ingot mold is lifted.

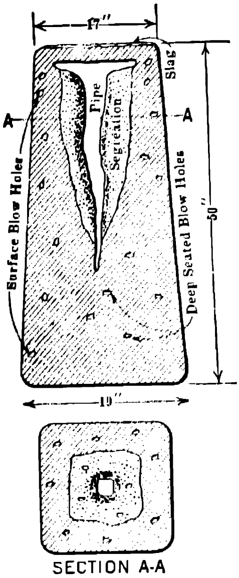


Fig. 2.—Defects in Ingots.

The following defects are present to some degree in all ingots: *pipes*, *blow-holes*, *segregation*, *slag*, and a very coarsely crystalline structure, termed *ingotism*. As the ingot cools the outside quickly forms a solid shell surrounding a molten interior. The shrinkage which accompanies the cooling of the interior produces a pipe. Blow-holes result from entrapped gases and from the solidification of certain impurities which shrink more than the iron in cooling. Segregation of the impurities is caused both from the rejection of impurities by the exterior as it solidifies and also by the differences in density, the impurities being lighter than iron. These defects are idealized in Fig. 2. Ingotism is produced through slow cooling from a very high temperature.

A long rectangular ingot cast on end makes a satisfactory form for rapid handling and for the initial roughing down in the rolling mill. Also, there is the tendency to concentrate the segregation of impurities and the pipe or cavity due to shrinkage in solidification to the last cooling portion at the center and top of the ingot. In making the best grades of steel the length of the pipe and badly segregated region can be much reduced by extending the top of the ingot mold with a ring of refractory material. Thus a reservoir of hot metal, or a "hot top," is formed into which the pipe and segregation is largely withdrawn.

Removal of the head of the pipe, most of the slag, and much of the segregated metal can be made by cutting off, or "cropping," the upper portion of the ingot. The evil effects of blow-holes and ingotism can be greatly reduced by proper mechanical treatment at high temperatures.

607. Heat Treatment of Ingots.—Rolling or forging of the ingot immediately after stripping is not satisfactory. If the outside is at proper temperature, the inside is so hot that there is liability of squirting out of the fluid interior when pressure is applied; while if the interior is at rolling temperature, the exterior is too cold.

A uniform temperature of the proper degree is obtained by inserting the ingots in soaking pits and holding them there until required for rolling. These pits are gas-fired furnaces equipped with regenerators for conserving the heat of the waste gases. This procedure also provides a regular supply of ingots to satisfy the continuous requirements of the mill, despite the intermittent delivery of the furnace; and no confusion, in case of accident or delay at either mill or furnace, will result.

608. General Method of Rolling Shapes.—When an ingot is inserted between two revolving rolls it is drawn through them in the direction of rotation, and at the same time there is downward and upward pressure upon the metal, and a pull in the direction of travel, which results in a reduction of thickness, a slight increase in width, and a material increase in length. A pair of simple rolls would in a single pass reduce an originally square bar to a rectangular one of even thickness equal to that of the distance between the rolls; the width, on the other hand, is slightly greater than the original, and of somewhat irregular and bulging outline, due to the downward pressure without side restraint. By a second pass through the same rolls, this time edge on, a square bar is obtained of dimensions equal to the distance between rolls, and of increased length in proportion to the amount of reduction of original section. By successive passes through rolls of varying distances of separation, or by adjusting the center distance of a single pair of rolls, and by quarter turning, or edging the piece as required, a square or rectangular bar of uniform cross-section may be rapidly produced.

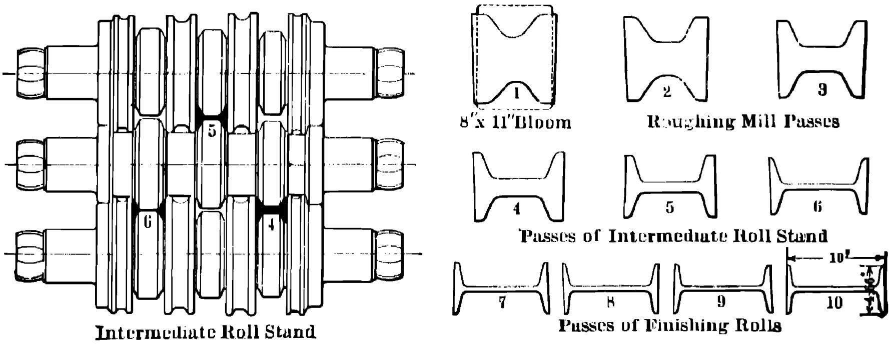


FIG. 3.—Typical Roll Passes in Forming a 10-inch I-beam. (Illinois Steel Co.)

Or the same result may be obtained in rolls of fixed center distance, which have grooves turned in their surfaces of proper dimensions for the successive reductions. Again, by varying the character of the grooves, a wide variety of cross-sections can be produced. Fig. 3 illustrates types of rolls used in forming I-beams. It also shows the shapes assumed by a bloom as it is gradually reduced to an I-beam.

609. Rolling Mills.—Rolling mills have been developed from the original type with a single pair of rolls, or two-high stand. Such an arrangement has a limited capacity, since succeeding passes are made only by sending the piece back idle over the roll stand, with consequent loss of time and heat. The three-high mill has been adopted for the rolling of most standard shapes. It consists of three rolls with their axes in the same plane, and so driven that by passing the bar through the lower pair in one direction, and through the upper pair on the return, reduction is obtained in both directions. For sections of great weight requiring very heavy mills with rolls of large diameter, the lift from lower to upper passes becomes impracticable; but rolling in each direction is accomplished by reversal of rotation of the two-high stand after each pass. In rolling rods or other shapes of very great lengths, there is much loss of time and cooling of the piece, even in three-high mills, if each pass is begun only after completion of the preceding one. By looping the rod back through the next pass as soon as the entering end comes through the rolls, several reductions may be effected simultaneously on the same rod, with great saving in time and heat. The capacity of the "looping mill" may be obtained by the "continuous mill." In this case the several stands of two high rolls are set in tandem, and properly geared to speed up successive passes to take care of the increased length of bar resulting from each reduction. The "universal mill" has a set of small rolls with their axes vertical; by varying the center distances of horizontal and vertical sets of rolls, a great variety of flat sections can be produced without multiplicity of rolls.

Ingots are rolled into blooms or billets, usually a rectangular or square form 10 by 10 to 2 by 2 in. in cross-section, on two-high reversing mills. The billets are sheared to the length required in the subsequent rolling operation, and are usually reheated.

Rolling mills have undergone much development, with resultant increase of output and elimination of hand labor. Heavy material is fed into the rolls by geared roller tables, and these tables in turn are made of the lifting, tilting, or transfer type to raise the bars from lower to upper passes or transfer them to others in different stands of the same mill train. The power required for driving varies from a few hundred to several thousand horse-power; heavy mills are usually driven by direct connection to steam engines, while electric motors have had much application for smaller mills, and especially for auxiliary equipment. The output of mills varies greatly. With light sections such as thin sheets and strips it may be as low as 10 tons per twenty-four hours; while certain mills will produce 4000 tons of billets or rails in the same period.

Most standard sections—rails, I-beams, channels, angles, round and square bars, etc.—are produced in three-high mills with rolls of fixed center distances and grooved to the special shapes.

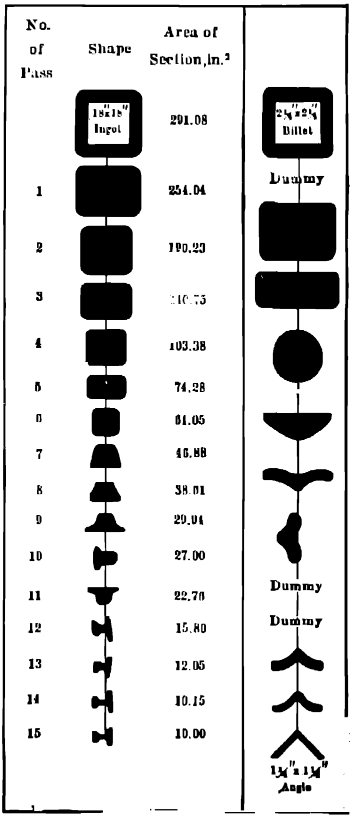
The successive passes through the rolls from ingot or billet to finished section are given in Fig. 4 for typical shapes. In the design of the successive passes, the aim is to effect not only the reduction with maximum speed and efficiency, but at the same time to so shape the grooves or turn the bar that work will be done uniformly upon all sides of the piece. Speeds of travel through the rolls range from 60 ft./min. for ingots to 600 ft./min. in the finishing pass.

Specialized lines of manufacture include plates, sheets, pipe and wire.

610. Plates.—Plates are of $\frac{1}{4}$-in. thickness and upwards. The ingot is rolled into a rectangular slab of cross-section sufficient to produce the length and thickness of plate desired. The slabs are cut to a length approximately equal to the width of the plate to be rolled. These slabs are reheated, and put through a two-high reversing or special three-high mill with flat rolls; the long side of the slab being parallel to the roll axes. The rolls are screwed down in successive passes until the plate has been reduced to the required gauge. After cooling it is straightened in special rolls and sheared to size.

Rolled plates may be obtained up to 2 in. in thickness, in widths up to 186 in. Maximum lengths range from 20 to 125 ft., depending on other dimensions.

611. Sheets.—Sheets are thin plates from $\frac{1}{100}$ to $\frac{1}{4}$ in. in thickness. Billets are first rolled into sheet bars of rectangular section $\frac{1}{2}$ by 8 to 1 by 10 in., on three-high mills. The sheet bars are cut to a length equal to the width of sheet to be rolled. After heating, a pair of bars are rolled at the same time, but separately, on a two-high mill with plain rolls, and with hand handling and screw downs to regulate thickness. After some reduction, the two pieces are rolled together, one on top of the other until too cold for further work. From two to four sheets are then placed in a pack, doubled by bending transversely and stamping flat, and reheated. The pack of four to eight sheets is rolled to gage, after which it is sheared and opened. The sheets are annealed, and then given the various surface finishes or coatings required in service.

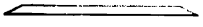


(*a*) (*b*)

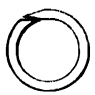
FIG. 4. Changes of Shape in Rolling (*a*) a 100-lb. Rail; (*b*) a 1¼×1¼ in. Angle. (*Iron Age*, Vol. 92, p. 968 and 1037.)

612. Pipes.—Pipes or tubes may be seamless, lap-welded, or butt-welded. Seamless tubes are made by piercing a round billet while it is being distorted by a set of special skew rolls; or by gradually pressing a plate into a closed end cup or tube. These hollow billets are drawn (hot or cold) to size over a mandrel and through dies. The principal outlet is for boiler tubes, bicycle tubing, etc., where maximum strength and lightness are desired.

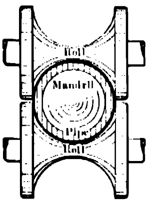
(1) SKELP WITH SCARFED EDGES



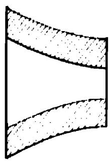
(2) SKELP ROUGHLY FORMED INTO PIPE



(3) WELDING BY ROLLING



(a) WELDING LAP-JOINT PIPE



(b) BELL THROUGH WHICH SKELP IS DRAWN TO FORM BUTT-JOINT PIPE

FIG. 5.

Lap-welded tubes are made from skelp, a flat strip rolled to proper thickness and of a width equal to the circumference of the pipe plus the lap, Fig. 5. The edges of the skelp are slightly beveled or scarfed to prevent too great an excess of metal at the lap. Up to 12 in. in diameter, bending to circular form is done by drawing the heated skelp through a bell-mouthed die; larger sizes are formed by putting the plate sidewise through a set of three bending rolls. The formed pipe is then heated to welding temperature and passed through a pair of rolls with grooves, corresponding to the outside diameter of the pipe. The roll pressure is resisted by a mandrel or ball on the inside of the pipe which is mounted between the rolls and on the end of a long rod. The pipe is then sized in grooved rolls and finished and straightened with a pair of skew rolls. Lap-welded pipe is used for boiler tubes and for steam and hydraulic piping to withstand high pressure and is made in diameters $1\frac{1}{4}$ to 30 in.

Butt-welded pipe is made from skelp which is welded along the butt joint without lap. The strips are heated to welding temperature; then drawn from the furnace through a bell mouthed-die, Fig. 5, which curls the strip to a circular form and forces the edges together with sufficient pressure to effect a continuous weld. The pipe is finished by passing through a pair of grooved sizing rolls. Butt-welded pipe is made in sizes from $\frac{1}{8}$ to 3 in. in diameter; it is used for gas and water pipe and miscellaneous purposes where not subjected to great pressure.

613. Wire.—Rods are rolled in looping or continuous mills to about a $\frac{1}{4}$ or $\frac{3}{8}$ in. in diameter, coiled into bundles, and pickled in acid to remove scale. Further reduction is effected by cold drawing through dies of high-carbon steel. The drawbench consists of the drawplate and a power reel for pulling the wire through and coiling. Successive reductions may be made on individual benches; or by multiple drawing in which case the coil is reeled only after reduction in several dies. A power reel is provided between each pair of plates around which the wire is given a couple of turns. After several reductions the wire becomes hard and brittle because of overstrain, and must be annealed before drawing can be continued. Speed of drawing is from 75 to 750 ft. per minute, depending on size and hardness of wire; reduction is from 20 to 25 per cent per hole.

614. Forging and Pressing.—Whereas it is only possible to roll members of uniform cross-section and for every change in cross-section it is necessary to provide a special set of rolls, forging provides a means of securing fine-grained, strong and tough parts of almost any required design. Forging requires little expense for special tool equipment but, on the other hand, on account of the length of time consumed does entail a much heavier fuel and labor charge than rolling. Since in forging the part is more completely under the control of the operator it is possible to finish it at just the right heat and to diminish the intensity of the blows in manner suited to securing a fine-grained product. The effect of the hammer blow, however, is not deep seated, consequently the process is best adapted to sections under 2 or 3 inches in thickness.

Small forgings may be made directly from ingots or from rolled bars. Ingots for small forgings are usually square or rectangular in form, those for large parts are cast in hexagonal sections with fluted surfaces. The latter type of ingot is less liable to crack in cooling than a square section. After cropping the remainder of the ingot is brought to a light red heat in a non-oxidizing flame and taken to the forge. Since the interior of a large ingot is often under high tensile stress due to cooling strains, reheating must be done at a very slow rate in order to avoid cracking. Often with ingots weighing many tons one or two days is required for reheating.

When the parts are of small size and the required number is small, reduction of the ingot or bar is accomplished by the hand hammer or sledge on the smith's anvil. If a large number of small parts are wanted *drop forgings* are made. They are formed between dies which are attached to the anvil and head of a steam hammer. In shaping intricate parts approach to final form is gradually made through the use of a number of sets of dies. Drop forgings are very commonly used in making various types of levers, wrenches, small connecting rods and crank shafts. They are superior to steel castings in quality on account of the mechanical work done upon them; but unless large quantities are wanted, they are more expensive due to high cost of dies.

Large forgings are reduced from the ingot under double-acting steam hammers which range in capacity up to 30 or 40 tons and are capable of striking 100 to 300 blows per minute. The ingot is clamped to a very heavy bar, called a porter bar, which is slung in an endless chain in such manner that the forging may be pushed backward or forward under the hammer, or rotated as desired. In making heavy shafting it is good practice to bore out the central portion of the ingot before reheating thus rendering it easier to heat and reducing the probability of cracking. When the ingot is forged, a long bar fitted with a head like a torpedo, called a mandrel, is thrust into the hole and kept under the hammer. As the ingot is revolved and hammered on the outside the mandrel acts as an anvil on the interior. In this manner the metal of the hollow section is rendered much more compact and uniform in structure and properties than is possible with a solid section. Forging is usually stopped when the color becomes a dull red. If further forging is required the part is again reheated to a bright red.

Pressing. Armor plate, cannon tubes, heavy shafting and other thick heavy masses of steel requiring mechanical treatment are most effectively worked under heavy hydraulic presses. The action of the press is much deeper than that of the steam hammer or the rolling mill. Furthermore, the press effects a reduction in size of large parts more quickly than the steam hammer. Presses range in capacity from 500 to 14,000 tons and are operated under pressures of 800 to 8000 lb. per sq. in.

615. Casting Steel.—Steel castings are most effectively used for intricate parts which cannot be rolled or forged and which must possess high strength and toughness; also when the required number of parts is small and the cost of equipment prohibits rolling or forging. With proper care in manufacture, castings can be made having strength equal to the rolled or forged product but somewhat inferior in ductility and toughness.

Steel castings are made from metal smelted by the crucible, Bessemer, open-hearth or electric furnace processes. For small and medium size castings of the very best grade, the electric furnace, or the electric furnace in conjunction with an acid Bessemer converter or basic open-hearth furnace, is superior to all other processes. It is, however, less adaptable to a wide variety of work than the crucible process, which is commonly used for very small castings of all grades and qualities. For the production of very large castings and for obtaining a large tonnage of standardized castings of medium size with continuous operation, the acid open-hearth furnace is very efficient and turns out an excellent product. The basic open-hearth process shares the same field of production, but makes castings somewhat inferior in quality and less costly than those gotten from the acid open hearth. For intermittent operation and a variable tonnage demand, the acid Bessemer process is well adapted. Baby converters of the Tropenas type are often used where the output is small. The quality of acid Bessemer castings is in general inferior to that which can be gotten from the other processes.

Patterns for steel castings are commonly designed with an allowance ¼ in. per foot for shrinkage. The castings are formed in green sand or dry sand molds which are made in much the same way as those used for cast iron (Art. 747). With steel castings, however, a good deal of care must be exercised to properly vent both molds and cores, to provide adequate gates for rapid filling of the mold, and to install a sufficiency of properly placed risers in order that the interior of heavy sections may be kept full of hot metal until the whole is frozen. Chills are sometimes used to hasten solidification during pouring and reduce blow-holes.

Owing to the great shrinkage of steel in cooling, intricate castings, or those which vary considerably in cross-section, must be separated from the mold as soon as the metal has solidified in order to prevent cracking. After the castings have been cooled slowly under sand or in a heated furnace the sprues are broken or cut off and the surfaces are freed from sand.

Steel castings which are to be subjected to heavy stresses should always be annealed for two to four hours at a temperature above the upper critical point (Art. 697). Annealing not only removes internal shrinkage stresses but also refines the grain and renders the casting stronger, tougher and more ductile. The toughness of castings of uniform section can be considerably increased by quenching in oil and reheating to a temperature just below the critical range.

616. Statistics.—The United States produces annually about 40 million tons of rolled steel shapes and one million tons of steel castings. Principal products are listed in Table 1.

TABLE 1.—TONNAGE OF PRINCIPAL IRON AND STEEL PRODUCTS OF THE UNITED STATES FOR 1936. (COMMERCE YEAR BOOK, 1937)

Class and Kind.	Thousands of Long Tons.
Total of rolled products	33,801
Rails, iron and steel	1,220
Sheets and plates	12,152
Wire rods	2,998
Structural shapes	2,898
Merchant bars	5,063
Reinforcing bars	1,029
Skelp, flue, and pipe iron or steel	2,157
Hoops	109
Band and cotton ties	38
Rolled forging blooms, billets, etc	473
Splice and tie plates	472
Hot rolled strips and flats for cold rolling	3,225
Blanks or pierced billets for seamless tubes	1,616
Wrought pipe	1,484
Seamless tubes	1,415
Cast iron pipe	960
Galvanized sheets	1,288
Tin and terne plate	2,355

CHAPTER XX

FORMATION AND STRUCTURE OF ALLOYS

Alloys in General

617. Reasons for Making Alloys.—In general, the properties desired in a metal to be used in engineering construction are not embodied to the best advantage in any single metal, and recourse is had to the mixing of two or more metals to attain the desired end. Such combinations of metals or metallic substances are classed as alloys, and they form one of the most important subdivisions of metallurgy.

618. Mixtures.—The properties of alloys are influenced not only by the nature and proportions of the components, but also by the character of the mixture. The constituents may form a simple mixture, coherent of course, but existing in the mass as distinct individuals. The properties of such a mixture are in large measure an average of those of the components, and vary with the relative proportions; this general relation may be modified by the relative adhesion of unlike particles as compared with the cohesion of the like constituents, and by the degree of fineness of the aggregate as affected by the nature of the components and physical conditions of manufacture. An important example in the iron-carbon alloys is pearlite, a mixture of ferrite and cementite.

619. Chemical Compounds.—In extreme contrast to the above, the components may have such a degree of affinity that they unite in atomic proportions to form a chemical compound, a new unit substance in which the individuality of the constituents is lost, and which may have physical properties distinct from and unrelated to those of the components of the alloy. Intermetallic compounds play an important role in the consideration of alloys, the carbide Fe_3C being of especial influence on the properties of steel.

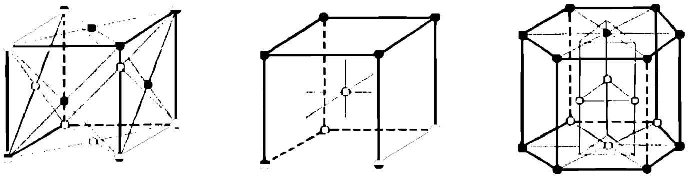
620. Solid Solutions.—The above-mentioned conditions are largely special, and represent the extremes or end relations in the possible degrees of miscibility of the constituents of alloys. Between is the wide gap in which the components are mutually soluble to the extent that they become blended into a homogeneous unit with loss of visible evidence (even microscopic) of isolation of particles, and yet where there is not that absolute loss of individuality which accompanies chemical union in atomic proportions. Solid solutions are important factors in the study of alloys; the resultant properties may differ in varying degrees from those of the components, according as the order of solubility approaches that of definite chemical union as a new compound. In the iron-carbon alloys, austenite, a solid solution of carbon in gamma iron, is an important example.

Constituents of an alloy may be only partially soluble; that is, solid solutions may result from addition of either component to the other up to certain limits of saturation, beyond which there results a simple mixture between these saturated solid solutions. Again, an intermetallic compound may form a simple mixture or a solid solution with the components of the mixture, or with a second compound of different atomic proportions in the same series of constituents.

621. Methods of Making Alloys.—Alloys may be made in various ways; those of greatest importance in the manufacture of materials for engineering construction are by fusion of the constituents and solidification after mixture, and by diffusion, where the body metal is in the solid state, and the diffusing material is solid, liquid or gas. The first-named method is most common and is employed where uniformity of material is desired throughout the entire section; the latter is chiefly of value in imparting a surface differing in composition and properties from those of the body material proper. In the formation of alloys by fusion, complete solubility of the constituents in the liquid state is usually desired; otherwise differences of specific gravity of the components will result in liquation and consequent irregularities of composition throughout the mass. But the solubility of metals is a function of temperature, pressure, and particularly of the state of the constituents. Thus, while there may be perfect miscibility while fusion exists, solidification may result in a solubility which is complete, partial, or nil. Perfect homogeneity of liquid is no criterion of structure in the solid; the latter may be homogeneous or heterogeneous —a solid solution or a simple mechanical mixture. Furthermore, the degree of miscibility, or especially the limit of saturation, being a function of the temperature, may alter by diffusion with changes of temperature below that of solidification. Diffusion in the solid state is, however, comparatively slow, and it is only by the maintenance of relatively high temperatures for long periods of time that alterations of structure occur. Such alterations are not usual in customary service.

622. Allotropy.—Certain metals while in one state, such as the solid, undergo at definite temperatures reversible changes in some of their physical properties which are usually accompanied by changes in the crystal structure. Such changes are called "allotropic." A solid alloy, which has as one of its constituents a metal exhibiting allotropy, may undergo transition in passing through the temperature normal for such allotropic change. Iron undergoes allotropic modifications in the solid state, and these are of extreme importance in heat-treatment processes.

623. Crystalline Structure of Metals.—By means of X-ray analysis it has been shown that the atoms in metals arrange themselves so as to form minute crystals of regular geometrical outline. In metal crystals there are commonly found three simple atomic arrangements, known as face-centered cubic, body-centered cubic, and hexagonal close-packed. In the face-centered cubic arrangement there is one atom at each corner of the cube and one atom at the center of each face (Fig. 1*a*). The body-centered cubic arrangement has atoms at each corner and one atom at the geometrical center of the cube (Fig. 1*b*). In the hexagonal close-packed arrangements (Fig. 1*c*), an atom is located at each prism corner and at alternate prism centers.*



(*a*) Face-Centered Cubic (*b*) Body-Centered Cubic (*c*) Hexagonal-Close-Packed (After Hull)

FIG. 1.—Common Atom Arrangements in Metals.

Solidification from a melt, in the case of a single, pure metal, will be by formation of numerous small definitely formed crystals in those parts of the melt which have reached the freezing temperature, which is a constant for the single metal. Upon these crystals as nuclei, others will build as solidification progresses, attaching themselves regularly with crystal faces together, and making up aggregates, each of which has a resultant orientation of axes of crystallization dependent upon the purely accidental position of its nucleus in the melt. As solidification approaches completion, there will be interference to further growth along lines of contact between different aggregates, and with complete solidification, a single pure metal will consist of a large number of grains, with irregular boundaries resulting from the contact lines of the individual crystalline aggregates which constitute the several grains. A typical structure of this character is shown in Fig. 2. Although the structure, the strength, and other properties are those of the single metal, variations may result from differences in average size of grains. This in turn may be influenced by cooling conditions which affect the number and distribution of nuclei of crystallization. Variations in properties may also be caused by differences in the relative cohesion along the contact faces of the crystals making up the individual grains, as compared with that along the boundaries or contacts between the separate aggregates or grains.

* For further study see *The Science of Metals*, by Zay Jeffries and R. S. Archer.

624. Effects of Solubility Relations in Alloys.—When two or more metals are mixed to form an alloy, solubility relations have great influence upon the progression of freezing and the structure of the resultant alloy. If the relations of the constituents are such that chemical combination results, and the amounts are of proper atomic proportions, solidification will progress in a manner entirely similar to that of a single pure metal. An intermetallic compound is essentially a unit substance; it will freeze at constant temperature, and it must exhibit a homogeneous structure consisting of a mass of grains, each composed of an aggregate of uniform crystals.

With relations of solubility other than that of chemical combination, solidification proceeds selectively, and is almost always spread over a range of temperature, as distinguished from the constant freezing temperature of a single metal. In subjecting a material to conditions which tend to change its state, there is a resistance opposed by the substance which tends to counteract such transition. In the case of a single substance, this is by sacrifice of part of the mass, which in freezing liberates its latent heat of solidification and thus, by a tendency to hold up the normally falling temperature, tends to keep the remainder of the mass in a liquid condition. With two or more metals in mixture, there is the possibility of resistance to change of state by liberation of heat during freezing of a portion of the mass, as noted above for a single metal; in addition there is the added possibility of sacrifice of some portion of the mass, which differs in composition from the body material in the direction of a higher temperature of freezing. Thus there is enrichment, by such selective freezing, of the remaining portion of the melt in the direction of a composition of lower temperature of solidification, and a resistance thereby to the external conditions tending to promote solidification.

FIG. 2.—Photomicrograph Showing Crystalline Structure of Swedish Iron.

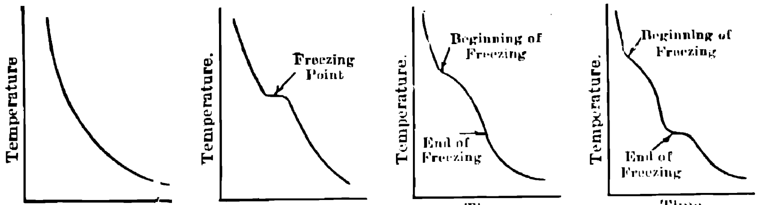
The structure of the alloy will be influenced by its method of freezing and the solubility relations; the former is, however, a function of the latter, and thus relations of solubility of the solidified constituents of the alloy are governing factors in the final structure. Assuming complete solubility in the solid, freezing will proceed by progressive selection, and will be spread over a range of temperature, as noted above. However, the assumed condition of solid solution implies that initial heterogeneity, because of progressive selection, should be effaced by diffusion, and the resultant alloy should, therefore, exhibit a homogeneity of structure of the granular type characteristic of the single pure metal or the intermetallic compounds. But interdiffusion of solid particles is likely to be relatively slow; thus by rapid cooling of the alloy through and below the freezing range, opportunity for such blending to a homogeneous mass may be checked to a greater or lesser degree, and a heterogeneity, varying throughout the individual grains from the composition of the first frozen particle to that of the last, may result in the solid alloy.

With solubility nil between the constituents of an alloy, resulting structure must be heterogeneous. Freezing from the melt will be by selection, with solidification of that one of the constituents which will, by its elimination, progressively enrich the melt in composition towards that of lowest freezing-point. This first portion to freeze will have an opportunity to solidify with considerable definiteness and regularity with respect to its crystal form, and without interference between the individuals, since there is freedom for movement in the remaining liquid. This liquid is finally forced to composition of lowest and final freezing temperature—the so-called eutectic temperature and composition, and constant for a particular alloy—when it will solidify and occupy such space as may remain between the particles making up the portion frozen during selection. Again, however, because of lack of solubility between the solid constituents, the eutectic portion must separate into its individuals on solidfication and in itself must be heterogeneous.

625. Methods Used to Determine Constitution Diagrams.—In order to construct constitution diagrams for alloys, it is necessary to secure considerable experimental information and to interpret it in accordance with the principles of the phase rule. Some of the more important methods used to secure such data are: thermal analysis, microscopic examination, magnetic and dilatometric measurements. The thermal methods are probably the most important. They are based upon the principle that changes in state of a substance are accompanied by change in its internal energy content, which is manifested by an absorption or liberation of heat. A body without transitions in the temperature range will absorb heat from surroundings at higher temperature, or radiate heat to surroundings at lower temperature, with perfect regularity, and a graphical representation, plotted as a function of temperature and time, will show an approximately logarithmic curve without breaks from smoothness or regularity. Should there be a change of state within the temperature range of investigation, the accompanying absorption or liberation of heat will cause a deviation from the normal law of heating or cooling, and such transition will be manifested by a jog or break from the normal curve extending over a time interval equal to that of heat absorption or liberation due to the transition. A familiar example of the above is the arrest of temperature during melting or freezing of a single pure substance.

By inserting a sensitive pyrometer into a molten alloy of any desired composition, and noting the temperature-time variations during normal cooling and solidification to atmospheric temperature, a "cooling curve" may be plotted which will be a record of the internal condition of the particular alloy within the temperature range employed. Changes of state and allotropic changes will be indicated by breaks from a smooth curve for intervals of temperature and of time corresponding to such transitions.

626. Cooling Curves.—Explanation of the construction of constitution diagrams will be presented simply by means of the ordinary temperature-time curves, such as shown in Fig. 3*a* to 3*d*. The freezing of a single pure metal, an intermetallic compound, or the eutectic portion of an alloy which solidifies at constant temperature, introduces the arrest illustrated in Fig. 3*b*, over a time interval corresponding to the liberation of the heat of solidification. In an alloy where the freezing is selective, the progressive shift of composition distributes the process over a range of temperature. For complete solubility in the solid, shown in Fig. 3*c*, the progressive solidification of particles which are solid solutions of two or more constituents, and the blending of these into a homogeneous unit as freezing proceeds, results in gradual approach of the break in the cooling curve to the normal with progressive elimination of the liquid portion. Where solubility is nil between the solid constituents, selective freezing introduces a break similar to that of the solid solution type while such selection proceeds. But since the solid portion now consists of one pure substance alone, the shift in composition of the liquid is to a portion—which may be the other constituent of a two-component mixture, but is usually some fixed, intermediate mixture of the two—which solidifies at constant temperature. The form of cooling curve is shown in Fig. 3*d*. For the particular metal under investigation, a cooling curve which exhibits freezing over a range of temperature without arrest at constant temperature denotes complete solubility in the solid; where freezing is spread over a range of temperature with final solidification at a constant temperature,



(*a*) No arrest or transition. No freezing.

(*b*) Freezing of pure metal or alloy of eutectic composition.

(*c*) Selective freezing of alloy with complete solubility.

(*d*) Selective freezing of alloy with eutectic arrest at end.

FIG. 3.—Typical Cooling Curves.

solubility is nil between the solid constituents, or the composition is beyond the saturation limits of an alloy of partial miscibility; with constant freezing only, the metal is a single pure substance, an intermetallic compound, or the eutectic mixture of an alloy with solubility nil or partial between the two components.

BINARY ALLOYS WITH LIQUID SOLUBILITY PERFECT, SOLID SOLUBILITY NIL

627. Significance of the Freezing-point Diagram.—Many cooling curves such as shown in Fig. 3*d* can be obtained for alloys of progressively varying composition and can be drawn on one diagram. Then, if lines are drawn through the critical points as shown in Fig. 4*a*, the constitution diagram for the two given components is obtained. Composition of the two components, *W* (white) and *B* (black), is indicated on the horizontal axis, and temperature on the vertical axis. The line *CED* indicates commencement of solidification and is called the liquidus, while the line *FEG* indicates completion of solidification and is called the solidus. The region above the line *CED* is a liquid solution of *W* and *B*, while everything below the line *FEG* is completely solidified. The region between the two lines is the freezing range and contains both solid and liquid.

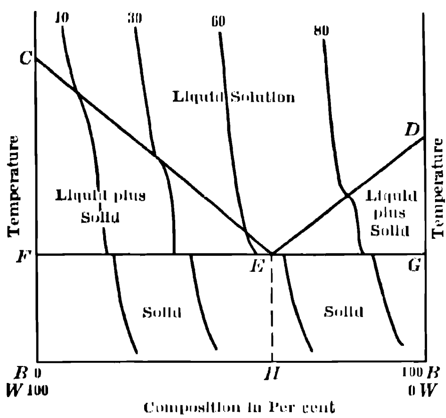


FIG. 4*a*.

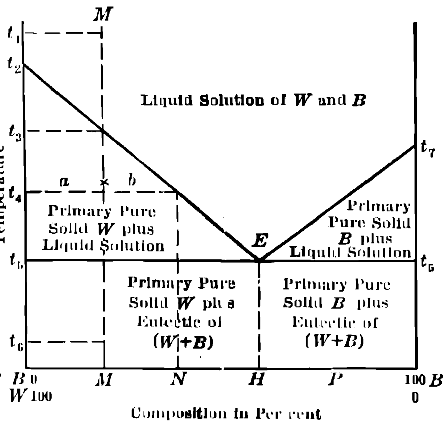

M
t_1
t_2
t_3
t_4
t_5
t_6
t_7
Liquid Solution of W and B
a
b
Primary Pure Solid W plus Liquid Solution
E
Primary Pure Solid B plus Liquid Solution
Primary Pure Solid W plus Eutectic of (W+B)
Primary Pure Solid B plus Eutectic of (W+B)
Temperature
B 0
W 100
M
N
H
P
100 B
0
Composition in Per cent

FIG. 4*b*.

Liquids miscible & solids unmiscible.

That solubility is nil in the solidified alloy is indicated by the fact that the line *FEG*, marking the completion of solidification, extends completely across the diagram. Thus, whatever may be the composition of the alloy chosen in the series *W*–*B*, completion of solidification will always be at a constant temperature *F*–*G*; and this, in turn based upon interpretation of experiment, and particularly upon the deductions of the

"Phase Rule," is evidence of a lack of solid solubility between the components *W* and *B*.

The solidification temperatures of *W* and *B* are at *C* and *D* respectively. A feature of interest is that upon addition of *W* to *B*, or *B* to *W*, freezing begins at progressively lower temperatures with each addition of the second element, until finally a composition *H* is reached at the intersection of *CE* and *ED*, which has the lowest freezing temperature of any alloy of the series, and one which is usually below that of either of the constituent metals. This marks the so-called "eutectic point" of composition and temperature, which is constant for the particular alloy series, but need not be, in fact usually is not, at a composition of definite atomic proportions of the components.

628. Behavior of Alloys in Freezing.—Two important rules applying to the two-phase portions of constitution diagrams will now be considered.

Rule 1 states that if a horizontal line is drawn through a point, *x*, of definite composition and temperature, in a two-phase field, such as the solid plus liquid field of Fig. 4*b*, the intersections of this line with the boundaries of the field will give the compositions of the two phases in equilibrium with each other at the given temperature.

Rule 2 provides information as to the relative amounts of the two phases present at any temperature within the two-phase field.

On the horizontal line indicated in Rule 1, the relative weights of the two phases, such as solid and liquid in Fig. 4*b*, are represented by the lengths of the horizontal line from the given point, *x*, to the liquidus and to the solidus lines respectively. This relationship may be seen to be qualitatively true by noting that as the temperature decreases the length of the line representing the relative weight of the solid increases while that representing the relative weight of the liquid remains the same. Hence the ratio of solid to liquid is shown to be increasing, as it obviously should be.

In discussing the changes that take place in an alloy of composition *M*, Fig. 4*b*, as it cools from the liquid state to room temperature, it is assumed that the cooling rate is slow enough for equilibrium conditions to be maintained at all times. This alloy at a temperature t_1 is a homogeneous liquid solution of *W* and *B* and will remain so until the temperature has dropped to t_3, at which point freezing must begin. According to Rule 1 the first particle that freezes out of solution must be pure *W*. As the temperature falls, more of the *W* component freezes out, while the liquid becomes richer in component *B*. Investigation of the conditions at temperature t_4 shows that the solid particles freezing out are *W*, while the composition of the liquid is represented by *N*. Application of Rule 2 at this temperature indicates that the ratio of solid weight, *W*, to liquid weight, *W* plus *B*, is given by b/a. From t_4 to t_5 more *W* continues to freeze while the liquid composition approaches the eutectic *E*. At a constant temperature of t_5 the last residual liquid of composition *H* solidifies to form the eutectic while the primary pure W does not undergo any change. The eutectic formed is a mixture of W and B crystals, each definitely visible at high magnification under the microscope. From t_5 down to room temperature there is no further change, and the resultant alloy has a heterogeneous structure of large primary W crystals plus eutectic areas, which as previously indicated are themselves heterogeneous.

The mechanism of cooling of an alloy of composition P is similar to that of the alloy just discussed, except that the primary solid that freezes out is now pure B instead of pure W. In the solid plus liquid range, more and more pure B freezes out as the temperature drops while the liquid composition gradually approaches the eutectic. At a constant temperature of t_5 the residual liquid again freezes to form the eutectic. The final structure in this case would consist of large primary B crystals plus the eutectic of W and B. The eutectic alloy, composition E, will not freeze on cooling until the temperature t_5 is reached. At this constant temperature complete solidification will take place and a structure entirely eutectic will be formed. It should be noted that, regardless of alloy composition, final freezing always takes place at temperature t_5.

If a fast-cooling rate is used instead of the slow rate assumed, the resulting structure will be finer in both primary crystals and eutectic, but there will be little change in the relative amounts of each. A fast-cooling rate will also tend to reduce segregation of the primary crystals.

629. Structures of Alloys of Perfect Solubility—Solid Solubility Nil.—An alloy structure of definite type will accompany the method of solidification outlined above. Assuming W to crystallize as cubes, such portion of this constituent as solidifies during the period of primary selective

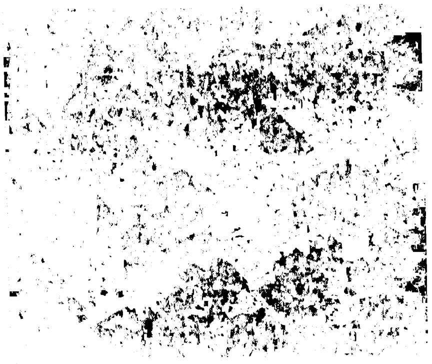


FIG. 5a.—Photomicrograph of an Alloy of Equal Parts of Lead (B) and Antimony (W). Shows cubes of excess antimony in a eutectic of lead and antimony.

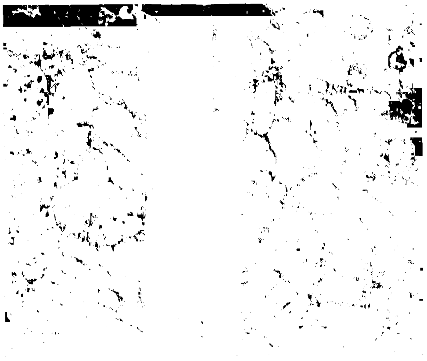


FIG. 5b.—Photomicrograph of an Alloy of Antimony (W) and Lead (B) Containing 95 Per Cent Lead. Note the oval black areas of lead surrounded by the eutectic network.

freezing) will make up a ground mass of white cubes, being free to build up on the cubical nuclei of initial crystallization because of the relative mobility of the remaining liquid portion during the temperature range of selective crystallization. The eutectic, on the other hand, will occupy the space remaining after the interval of primary crystallization, but will exist in this area as a composite granular or lamellar structure of white and black particles. For all alloys on the *W* side of the eutectic proportions, *W* will be the excess substance, exhibiting primary crystallization; while all of the *B* constituent will appear in the eutectic. The relative proportion of primary constituent *W* and eutectic will depend upon the initial composition of the alloy; the more rich it is in *W*, the less will be the relative quantity of eutectic.

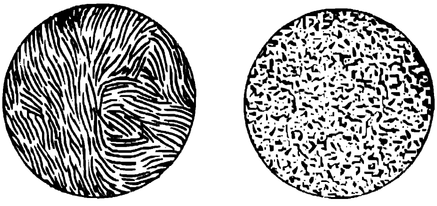


Fig. 6.—Lamellar and Granular Types of Eutectic Structure.

A typical structure is shown in Fig. 5*a*. The white cubes of *W*, exhibiting various polygonal shapes depending upon the purely chance form of orientation and distribution of the cubes, and the plane of cutting of the section, are imbedded in a granular white and black eutectic of relatively finer state of aggregation of both *W* and *B*.

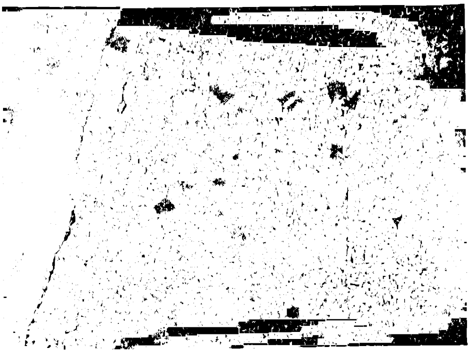


Fig. 7.—Photomicrograph Showing Eutectic Alloy of 13 Per Cent Antimony and 87 Per Cent Lead with a Few Segregated Antimony Crystals.

All alloys on the *B* side of the eutectic proportions (*B* is in this case called the excess substance, regardless of the particular weight relations) will exhibit a structure of black aggregates of regular outlines due to primary crystallization, together with a composite black and white granular or lamellar eutectic, the latter similar in all respects to that characteristic of the *W*-rich alloys described previously. The typical structure is shown in Fig. 5*b*, assuming *B* to form aggregates of oval form.

Should the initial alloy be of eutectic composition, there will be no primary crystallization of either *W* or *B*. The structure will be entirely eutectic of either granular or lamellar type (see Figs. 6 and 7).

630. Summary for Alloys with Solid Solubility Nil.—To summarize, binary alloys of the type where solubility is complete in the liquid state, and nil in the solid, are characterized by the presence of a eutectic throughout the series. All intermediate alloys, therefore, solidify at temperatures lower than those of the two constituent metals, except for the unusual limiting case where the eutectic point is at the end of the series coincident with the constituent metal of lowest freezing temperature. Freezing is spread over a range of temperature and is rigidly selective throughout the series, with primary crystallization of that component which is in excess of the eutectic proportions. The eutectic occupies the areas remaining after primary crystallization, and its quantity is inversely proportional to the distance of the particular alloy from the eutectic composition. The eutectic always solidifies at constant temperature, is always of constant proportions, which are only coincidentally of atomic ratios, and is a composite of relatively finer state of aggregation than the excess metal of primary crystallization. All alloys of the series are heterogeneous throughout, and consist of an excess substance, which may be either pure metal, plus the eutectic. Typical alloys of this series are lead-antimony and lead-tin.

BINARY ALLOYS WITH LIQUID SOLUBILITY PERFECT, SOLID SOLUBILITY PERFECT

631. Typical Constitution Diagram.—The assumption of a solubility in the solid state, which is complete throughout the entire alloy series, implies of necessity perfect homogeneity of structure. Experimental evidence, however, indicates selectiveness during freezing, with consequent heterogeneity which is effaced only after solidification.

A typical constitution diagram is given in Fig. 8, plotted in the customary manner as a function of temperatures for ordinates against composition abscissae for two components *W* (white) and *B* (black). The liquidus and solidus, as determined by transition points noted on cooling curves taken for various compositions within the series, are given by the lines *CnD* and *CoD* respectively. The region above the liquidus will be a homogeneous liquid solution of *W* and *B*. Between the two lines is the region of selective freezing containing both liquid and solid solutions of *W* and *B*.

632. Behavior of a Typical Alloy in Freezing.—Again cooling is assumed slow enough for equilibrium to obtain at all times. For an alloy of composition *X*, Fig. 8, freezing will begin when the temperature falls to t_2. Rule 1 indicates that the composition of the first frozen crystal is represented by *F*. Since there is complete solubility in the solid state, this particle will be a homogeneous blend, a solid solution of *W* and *B*, which has no tendency to split up into its constituents.

As the temperature drops to t_3 the composition of both solid and liquid is constantly changing and more crystals are being formed. At t_3 application of the two rules indicates that the composition of all the solid is represented by *G*, while that of the liquid by *K*, and that the ratio of solid weight to liquid weight is given by b/a. Because of the solubility in the solid state the crystals formed during the drop in temperature from t_2 to t_3 tend to diffuse into a homogeneous unit and to draw enough *B* from the liquid to enrich the resultant blended solid to composition *G* at t_3.

Freezing continues as the temperature drops from t_3 to t_4, resulting again in constantly changing liquid and solid compositions and an increasing amount of solid. If, as has been assumed, diffusion of the solid particles has kept pace with their crystallization from the melt, solidification will be complete at t_4. The last liquid portion just before complete solidification will have the composition *L*. The solidified alloy will be a homogeneous light gray solid, and will have a composition *X*, which is identical to that of the original liquid. After complete solidification no further change will take place from t_4 down to room temperature.

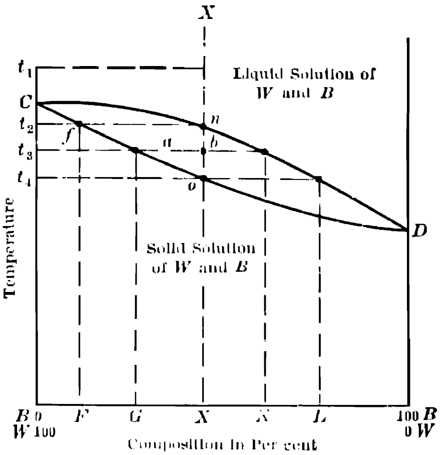


FIG. 8.

Should diffusion in the solid fail to keep pace with the rate of crystallization, freezing will not be completed until the melt has reached a composition between *n* and *D*; the last frozen particle will in this case have a composition between *o* and *D*. And because of lack of diffusion of the solid particles, the resultant alloy will exhibit a heterogeneity in the individual grains, progressively shading in color from the lighter gray of a nucleus of *W*-rich material of composition somewhere between *f* and *o*, to a relatively darker gray of the last freezing portions of *B*-rich material of composition between *o* and *D*. The extreme or limiting condition, provided no diffusion in the solid resulted, would be a nucleus corresponding to the first frozen material *f*, shading progressively to *B*, marking the boundaries of the individual grains. But in all cases, the structure should exhibit a mass of grains, similar to that of a pure metal (Fig. 2); with each grain a crystalline aggregate having the homogeneity of a solid solution under ideal conditions, but actually approaching this only to the degree that diffusion in the solid has effaced the heterogeneity resulting from selective freezing.

Attainment of homogeneity depends upon the characteristics of the constituent metals, and upon the condition of cooling. Since diffusion in the solid is relatively much slower than in the liquid state, slow cooling at temperatures just below the solidification range is rather an essential condition to promote homogeneity; rapid solidification and cooling to normal temperatures, on the contrary, promote heterogeneity of the characteristic shading-off type discussed above.

633. Summary for Alloys of Perfect Solid Solubility.—To summarize, binary alloys of the type having complete solubility in both liquid and solid states, solidify by a process of selective freezing. This is not rigid, however, and the heterogeneity of structure resulting from such selection is effaced by diffusion, under ideal conditions of cooling; the final alloy is then a solid solution with homogeneity of structure. The so-called " onion peel " type of structure may result if cooling conditions are such that there is not complete effacement of the heterogeneity of selective crystallization. All alloys of the series must freeze over a range of temperature, and there can be no solidification at constant temperature corresponding to the eutectic of alloys of the immiscible type. Typical alloys of this type are: iron-manganese and antimony-bismuth.

BINARY ALLOYS WITH LIQUID SOLUBILITY COMPLETE, SOLID SOLUBILITY PARTIAL

634. Typical Constitution Diagram.—Partial solubility in the solid state implies perfect miscibility, with accompanying homogeneity of structure, at either or both ends of the series, up to particular limits of saturation. Beyond these limits, there must be separation of the constituents, and heterogeneity of structure. The relations are a combination of the two types previously discussed.

The conventional Greek letters are used as names of the solid solutions in the typical constitution diagram shown in Fig. 9. There are seven characteristic areas: I, the molten solution; II and III, the regions of selective crystallization containing α solid solution plus liquid and β solid solution plus liquid, respectively; IV and V the regions of solid solubility, α and β solid solutions, respectively; VI and VII, the regions beyond the saturation limits containing α solid solution plus the eutectic, and β solid solution plus eutectic, respectively. The limits of solid solubility are marked by the eutectic line *GEF*; that is, the presence of a eutectic is evidence of final solidification at constant temperature and composition, and of consequent separation, in accord with the deductions of the " Phase Rule," into the distinct constituents.

635. Behavior of Typical Alloys in Freezing.—An alloy of composition *U* will solidify entirely in accord with the method outlined for complete solubility. Freezing will start when temperature t_1 is reached, and the composition of the first solid crystal forming will be *L*. The solid freezing out of solution is neither pure *W* nor pure *B*, but a solid solution of both rich in *W*, which is called α solid solution. As the temperature drops, the composition of both liquid and solid is constantly changing, and more solid is freezing out. The composition of the last portion of liquid just before complete solidification at temperature t_2 is *M*. If a very slow rate of cooling has been maintained, the heterogeneity of the final structure due to the selective crystallization through the freezing range will be effaced by diffusion of the solid particles. The final structure at t_2 and down to room temperature will be a homogeneous solid solution of composition *K* and of light gray color due to the preponderance of white constituent *W*. The above discussion will hold for any alloy in the composition range *B*0 to *G*.

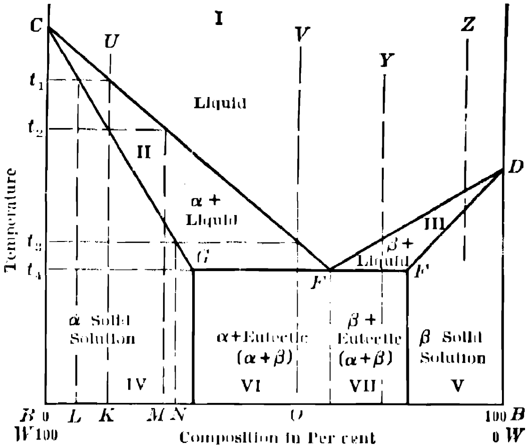


FIG. 9.

The above reasoning will hold, likewise, for the solidification of an alloy of composition *Z*. β solid solution, rich in the black constituent *B*, will freeze out, however, instead of the α solid solution, and the composition of the solidified alloy will be *Z*. The final structure in this case will be considerably darker than the *U* alloy because of the large amount of *B* present. As indicated in Fig. 9, the final structure for all alloys between *F* and 100 *B* will be β solid solution.

An alloy *V* will begin to freeze at temperature t_3, with separation of the first frozen particle of α solid solution with a composition *N*. As the temperature drops the composition of both liquid and solid is constantly changing, and more solid continues to freeze out. At t_4, assuming a very slow rate of cooling through the freezing range, diffusion of the solid particles plus extraction of sufficient *B* from the melt has resulted in a completely homogeneous solid solution of composition *G*. The last residual liquid at t_4 has the composition *E*, and final solidification proceeds at constant temperature accompanied by immediate separation of the solid constituents of the eutectic. Owing to partial solid solubility, the eutectic will not be a composite of the two pure components *W* and *B*, but will consist of a heterogeneous mixture of particles of *W* saturated with *B*, and *B* saturated with *W*; in other words, of a granular or lamellar composite of α solid solution. composition *G*, and β solid solution, composition *F*.

The final structure will therefore consist of a primary aggregate of composition *G*—a solid solution exhibiting its particular definiteness of crystallinity—together with a eutectic occupying the remaining area, and composed of a composite mixture of particles of composition *G* and *F*, each a saturated solid solution. The structure is heterogeneous, and is characteristic of all alloys between *G* and *E*; the differences between these alloys being in the quantitative proportions of primary substance with respect to eutectic, the amount of the latter increasing from 0 to 100 per cent as the composition of the particular alloy varies from *G* to *E*.

Alloys of composition between *E* and *F* solidify in a manner similar to those just discussed. The excess substance of primary crystallization is, however, a saturated solid solution of composition *F*, which will structurally exhibit its particular definiteness of crystalline habit. The eutectic will be identical in composition with that resulting in alloys from *G* to *E*; that is, a heterogeneous composite of two saturated solid solutions *G* and *F*. The quantity of eutectic will vary from 0 to 100 per cent as the composition of the original alloy is shifted from *F* to *E*.

Should the original alloy be of eutectic proportions *E*, solidification will not begin until the temperature has dropped to t_4. It will then proceed at this constant temperature, with accompanying separation of the two constituents *G* and *F* to form the characteristic granular or lamellar composite, making up the entire structure.

If a fast-cooling rate is employed, instead of the slow one which has been assumed, the α and β solid solutions will be heterogeneous instead of homogeneous. The composition from point to point will vary instead of being the same. Also, a fast-cooling rate will result in the presence of some eutectic in the alloys between *B*0 and *G*, and from *F* to 100 *B*.

636. Summary for Alloys with Solid Solubility Partial.—To summarize, binary alloys of the type where solubility is complete in the liquid state, and partial in the solid, are characterized by a eutectic for part of the series, and this eutectic marks the limits of solubility in the solid. Freezing is selective throughout the series. It is not rigidly so within the limits of saturation, and the heterogeneity of selective crystallization should be effaced by diffusion in the solid, and homogeneous alloys should result. Beyond the limits of solubility, the heterogeneity cannot be effaced by diffusion, and the resultant alloys consist of an excess substance of primary crystallization, plus a eutectic. The excess substance is a saturated solid solution, of either component of the series saturated with the other, depending upon the composition of the particular alloy with respect to that of the eutectic. The eutectic is a composite of the two components of the alloy series, each saturated with the other, and is always of the same composition for the particular series. All alloys of compositions within the limits of solubility are structurally homogeneous, provided cooling conditions have enabled diffusion to complete itself. Beyond the limits of solubility, the structure is heterogeneous.

Modifications in the form of solidification diagram for alloys of this type of partial solubility, are given in Fig. 10. The differences involved are only in details of progress of solidification, and not in the character of structure resulting. The reader is referred to treatises on metallography for detailed discussion of these modified forms.

Typical alloys of this class are those of aluminum and zinc, copper-silver, and cadmium-mercury.

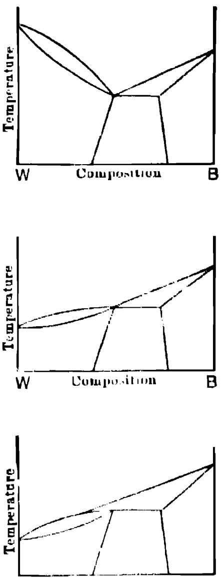


FIG. 10.

ALLOYS OF MORE THAN TWO COMPONENTS

637. Complexity Due to Metallic Compounds.—Additional complexity is introduced into the study of alloys by the presence of more than two components in the mixture and the possibility of formation of chemical compounds between the constituents.

If an intermetallic compound, for example, of the atomic proportions W_1B_1 forms in the alloy series W-B, this compound is a homogeneous, unit substance, and usually is unlike the constituent metals in its melting-point or general physical properties. It enters into alloying relations with W on the one hand, and B on the other. Virtually, therefore, W and B no longer have simple relations with one another; the series becomes a duplex one of W with W_1B_1 and W_1B_1 with B. There is a duplex set of solubility relations, each independent of the other. Fig. 11 illustrates such a series, in which W_1B_1 and W have a completely miscible relation in the solid state, whereas W_1B_1 and B form heterogeneous alloys because of lack of solubility in the solid. No alloys of the series will have free W and free B together. A second compound W_2B_2 would make the couples of the complete series $(W$-$W_1B_1)$, $(W_1B_1$-$W_2B_2)$.

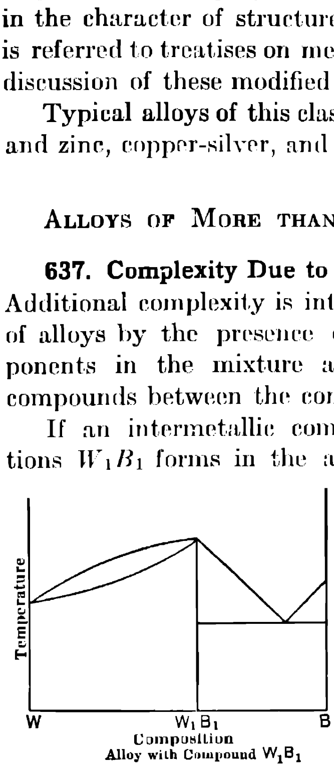


FIG. 11.

(W_2B_2–B), each in reality a binary series independent with respect to the others. The simplest method of treatment of a binary alloy with intermediate chemical compounds is to break the series into its component groups, and to consider each as a simple binary alloy having one of the three fundamental types of solubility relations discussed heretofore.

638. Difficulties Encountered with Several Components.—The consideration of alloys with multiplicity of components becomes increasingly difficult with increasing number of constituent metals. The possible groups of binary, ternary, etc., relations becomes very great, and it is an extremely arduous task to obtain all of the cooling curves needed to make up the complete constitution diagrams. The possible formation of complex chemical compounds also adds to the difficulty. Again, the graphical representation of the data becomes complex, or even impossible. For a ternary series, it is possible to represent the composition relations by means of triangular coordinates; and with temperatures plotted on axes perpendicular to this triangular plane, the solubility diagram takes the form of a space model in three dimensions, as compared with the two-dimension, plane diagrams of the binary alloys.

Much experimental data has been obtained for the relations in binary alloys; on the contrary, but little has been done for greater multiplicity of components. At the present time the most satisfactory method of treatment of the different industrial alloys, most of which have several component metals, is to consider first the binary relationships of the two important constituents, and subsequently deal with the modifying influences of the various secondary elements.

CHAPTER XXI

CONSTITUTION OF IRON AND STEEL

639. Necessity for Alloying Pure Iron.—Very little of the iron which is employed in engineering construction is pure; the greater proportion is purposely alloyed with one or more elements to improve the inherent properties of the iron. The most important alloying elements are: carbon, silicon, nickel, chromium, manganese, molybdenum, vanadium, copper, cobalt, tungsten, and aluminum.

640. Classifying Iron and Steel.—Dating from the time when all iron products were the result of primitive methods of manufacture, they were classed as (*a*) iron, material which would not harden appreciably on sudden cooling; and (*b*) steel, material which did harden by such treatment. Later, the nonforgeable cast iron came into the fold as a third variety of product. With the development of Bessemer and open-hearth methods, it became possible to make a product of such low carbon content that it did not harden any more than the older irons on quenching from a red heat. Yet there was a greater selling value attached to the name " steel "; there was the fact that the low-carbon material resulted from the modification of the merest details of manipulation of processes which equally readily made high-carbon product, or " steel "; and there was no sharp dividing line between the classes of material. Thus, the name " steel " became associated with the product of modern processes of manufacture; and has become rather firmly rooted in our nomenclature as covering all articles made by Bessemer or open-hearth methods, regardless of their inability to harden on sudden cooling.

The current usage in this country, as well as in England and France, is to classify as

(1) Wrought iron—the product of the puddling furnace or sinking fire, also the product of the Aston process.

(2) Steel—the product of the cementation process, or malleable compounds of iron made in the crucible, converter, or open-hearth furnace.

In Germany the effort has been to group the products more in accordance with their physical properties, and the soft steel of the converter and open-hearth processes is called " ingot iron."

The definitions which follow, unless otherwise stated, were proposed by a Committee on Nomenclature to the Sixth Congress of the International Association for Testing Materials in 1912.*

DEFINITIONS PROPOSED FOR THE PRINCIPAL FERROUS METALS

641. Cast Iron.—Definition. Iron containing so much carbon that it is not usefully malleable at any temperature.

Remarks. In America, besides the foregoing generic meaning, "cast iron" is used also in a specific sense which excludes "pig iron" (see below) and is restricted to cast iron in the form of castings other than pigs and to remelted cast iron suitable for such castings. The cast iron of commerce is reduced from the ore, usually in the iron blast furnace, in direct contact with solid carbon, and is then tapped from the furnace in a molten state. It always contains an important percentage of carbon, usually from 2.5 per cent to 4.5 per cent, and in most cases an important percentage of silicon.

There are three chief varieties of cast iron.

Gray cast iron: Relatively soft, and characterized by the presence of sheetlets of graphite, often forming an irregular skeleton. This is the variety used chiefly for engineering work.

White cast iron: Extremely hard and brittle, characterized by having all or nearly all its carbon in the combined state, and by its consequent lack of graphite.

Mottled cast iron: Intermediate between gray and white cast iron.

642. Pig Iron.—Cast iron which has been cast into pigs direct from the blast furnace or its equivalent. This name is also applied to molten cast iron which is about to be so cast into pigs, or is in a condition in which it could readily be cast into pigs.

643. Mixer Metal.—Molten cast iron which has been passed into or through a metal mixer.

Iron Castings.—Definition. Cast-iron castings.

Remarks. They are usually made either (1) by remelting cast iron in a cupola or other furnace, or in crucibles; or (2) from molten iron direct from the blast furnace.

644. Malleable Cast Iron.—The following definitions for *malleable cast iron* and *pearlitic malleable cast iron* were tentatively adopted by the American Society for Testing Materials in 1936 (see *A.S.T.M.*, Des. A196–36T.).

"*Malleable Cast Iron.*—Iron, white as cast, which has been made malleable by a heat treatment which has converted substantially all of the combined carbon into nodules of graphite."

"*Pearlitic Malleable Cast Iron.*—Iron, white as cast, which has been made malleable by a heat treatment which has converted some of the combined carbon into graphite, leaving, however, significant amounts of combined carbon in the product."

Author's note. In the above-mentioned types of malleable cast iron there is only a small removal of carbon by oxidation. In Europe certain malleable irons are made relatively free of carbon. This is accomplished by annealing white cast iron at high heat in an oxidizing packing for a long time. Malleable cast iron is neither a steel nor a cast iron. It differs from steel in being cast into a mass not malleable initially; it differs from cast iron in that it is rendered malleable by heat treatment after casting.

645. Wrought Iron.—Author's Definition. A malleable ferrous metal aggregated from solidifying particles of refined metallic iron with which, without subsequent fusion is uniformly mixed minute particles of ferrous silicate slag.

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* See *Proc. I.A.T.M.*, Sixth Congress, 1912, p. 145 of Sec. A.

Author's note. Wrought iron usually contains 2 or 3 per cent of slag but carries so little carbon that it does not harden usefully when suddenly cooled. Though occasionally made directly from the ore, wrought iron is usually made from pig iron by removal of sufficient carbon and silicon to convert the molten pig iron into pasty particles with slag intermingled.

The same end is attained in the Aston process by charging refined molten iron at a high temperature into molten slag at a lower temperature.

The pasty particles obtained in either process are then collected into a coherent mass, the excess slag squeezed out, and the puddle ball or sponge thus formed is rolled into shapes.

Although wrought iron adulterated with steel scrap is sometimes sold as wrought iron, such procedure is contrary to the intent of the definition (see also *A.S.T.M.*, Des. A 81–33).

In Great Britain the term "malleable iron" is often used in reference to wrought iron. This is bad practice, since such usage is likely to leave the lay reader in doubt whether wrought iron or malleable cast iron is meant. Clarity of meaning will be promoted by the avoidance of such expressions.

646. Steel.—Official Definitions. See "Carbon Steel" and "Alloy Steel" below.)

1. Fluid Origin.—Definition. Iron which is cast from the molten state into a mass which is usefully malleable initially at least in some one range of temperature. (See "Steel II," below.)

Remarks. Such metal is steel whether it can be hardened or not, whether it contains much or little or even no carbon, and for that matter even if it is chemically pure iron. It is sometimes called "ingot metal." With the exception of "blister steel" and its derivatives all the steels which have any present industrial importance including the "alloy steels" (see below) fall under this definition.

These steels have been divided into:

(*a*) *Ingot Iron.*—Steel with too little carbon to harden usefully on rapid cooling This name has never been widely used, and for a long time fell into complete disuse. It has lately been revived as a trade name. It should be avoided in scientific and technical writings because, with the iron-carbon alloys divided into the four great species, (1) wrought iron, (2) steel, (3) cast iron, (4) malleable iron castings, it is confusing to call a variety of "steel" "ingot iron."

(*b*) *Ingot Steel.*—Steel with enough carbon (say 0.30 per cent or more) to harden usefully on rapid cooling.

Steel made by melting in a crucible is called "crucible steel"; that made in an electric furnace is called "electric steel."

Steel II: Plastic Origin.—Definition. Iron which is aggregated from pasty particles without subsequent fusion; is malleable at least in some one range of temperature; and contains enough carbon (say 0.30 per cent or more) to harden usefully on rapid cooling from above its critical range.

Remarks. Blister steel and its derivatives and a few other high carbon steels which are important to-day, are the only present steels covered by this definition.

The British Members are unable to accept the official definitions and accept the following alternatives:

Steel: Iron either pure or associated with other elements which contains sufficient carbon to cause it to harden usefully when rapidly cooled from high temperatures and is so malleable initially, that it can be forged or rolled; also iron which has been cast from a molten state, which does not contain sufficient carbon to cause it to harden usefully when rapidly cooled, and is so initially malleable that it can be forged or rolled.

647. Blister Bar, Cement Bar, Converted Bar.—Official definitions. Steel of plastic origin made by cementing wrought iron with carbonaceous matter. Also, commercially, such steel when heated and worked into merchant sizes. Most writers have used "blister steel" in the former and broader sense. In Sheffield it is used solely in the latter and narrower sense.

Remarks. The blister steel of commerce is made by cementing very pure wrought iron with charcoal. The term Cemented Bar, may be applied in a general sense to any wrought-iron bar which has been subjected to a process of cementation.

648. Blister Steel.—Bars rolled or forged from blister bar. Many writers have used "blister steel" in the sense of "blister bar."

The British Members are unable to accept the official definitions and propose the following alternatives:

Blister Bar, Cement Bar, Converted Bar: Definition. High class Swedish or other wrought-iron bar of equal purity which has been subjected to a process of cementation in contact with charcoal, while introducing carbon into the iron also develops blisters on the surface of the cemented bar.

Blister Steel: Definition. A term sometimes used to describe cemented converted or blister bar which has been heated and worked into merchant sizes.

649. Plated Bar.—Definition. Bars of blister steel which have been rolled or hammered while hot.

Remarks. This treatment, which is usually applied to such bars broken to convenient lengths, flattens down their blisters and toughens the metal somewhat.

650. Single-shear Steel.—Definition. Shear steel made by welding a pile of plated bars into a faggot. Also the bars and other merchant shapes made by rolling of hammering such a faggot.

651. Double-shear Steel.—Definition. Shear steel made by piling, hammering, and thus welding bars of single-shear into a bloom. Also the bars and other merchant shapes made by rolling or hammering such a bloom.

652. Carbon Steel.—Definition. Steel which owes its distinctive properties chiefly to the carbon as distinguished from the other elements which it contains.

Remarks. Though among the alloy steels some are but moderately malleable, among the carbon steels industrial usage confirms the name "steel" to products malleable enough to be rolled or forged into merchant shapes.

653. Alloy Steel.—Definition. Steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other elements and carbon.

Remarks. Some of the alloy steels necessarily contain an important percentage of carbon, even as much as 1.25 per cent. There is no agreement as to where the line between the alloy steels and the carbon steels shall be drawn.

654. Ferro-alloys.—Definition. Iron so rich in some element or elements other than carbon that it is used primarily as a vehicle for introducing that element in the manufacture of iron or steel.

Remarks. The ferro-alloys are not usually malleable, and they usually contain more of the alloying element than is desirable in an alloy steel. With variations in industrial conditions the line between alloy steels and ferro-alloys must needs shift. Indeed, a substance might simultaneously be an alloy in the machine shop and a ferro-alloy in the steel mill.

655. Semi-steel.—A vague trade name for various products near the border line between steel and cast iron. Among these are low carbon cast iron made in the air furnace, or in the cupola furnace by the addition of steel scrap to the charge. Also a trade name for malleable cast iron.

While the report failed of adoption, because of considerable opposition, and does not represent, therefore, the official view of the Association, it conforms very closely with the consensus in the United States.

COMPOSITION AND CONSTITUTION

656. Composition of Iron and Steel.—Chemical composition of typical forms of iron and steel products finding utility in connection with engineering construction are given in Table 1. The much-used S.A.E. numbers for designating steels are described in Appendix B.

TABLE 1.—TYPICAL COMPOSITIONS OF IMPORTANT FERROUS METALS

METAL.	COMPOSITION IN PER CENT (IRON OMITTED).								
	C	Si	Mn	S	P	Ni	Cr	Va	Ti
Ingot iron (pure)	.01–.02	< .01	.01–.02	.01–.02	< .01				
Boiler plate	.10–.20	.05–.15	.30–.50	< .05	< .05				
Structural steel	.15–.25	.05–.25	.30–.50	.04–.06	.04–.10				
Structural steel (electric)	.15–.25	.05–.25	.50–.80	< .02	< .02				
Axles and shafts	.30–.40	.05–.25	.40–.80	< .06	< .05				
Vehicle springs	.90–1.0	.05–.25	.25–.50	< .05	< .05				
Rails	.40–.70	< .20	.60–1.0	< .06	< .10				
Carbon tool steels	.50–1.5	.10–.30	.10–.50	< .03	< .03				
Steel castings	.15–.40	.20–.35	.50–1.0	< .05	< .06				
Cast-iron castings	2.5–4.0	.70–2.5	.40–1.0	< .12	.20–1.2				
Nickel steel (structural)	.30–.45	.05–.25	.60–.70	< .05	< .05	3.5–4.0			
Manganese steel	1.0–1.3	.30–.80	11–14	......	< .06				
Transformer (silicon) steel	.05–.10	4.0–4.3	.10–.15	< .06	< .05				
Vanadium steel	.25–.50	.10–.25	.80–.90	< .05	< .05	.....	.....	.15–.25	
Titanium rail steel	.40–.80	.05–.10	.80–1.0	< .05	< .05	.....	.....	.....	.10–.20
Nickel-chrome steel	.20–.40	< .10	.30–.60	< .05	< .05	1.2–4.0	.60–2.0		
Chrome-vanadium steel	.20–.60	.10–.25	.50–.80	< .04	< .04	.....	.80–1.1	.15–.25	W
High-speed steels *	.60–.80	.15–.40	0–2.0	< .03	< .03	.....	3.0–5.0	.50–2.0	13–19
18-8 Stainless Steel	< .20	.50–1.0	< .50	< .045	< .045	7–10	17–20		
Low Alloy High Strength Steels								Cu	
Cor-ten	.10	.50–1.0	.10–.30	< .05	.10–.20	.....	.50–1.5	.30–.50	
Yoloy	.05–.25	< .30	.....	< .05	< .05	2.0	.....	1.0	
Jal-ten	< .35	.....	1.3–1.7	< .05	< .04	.....	.....	< .40	
Cromansil	.10–.45	.60–.90	1.0–1.4	< .05	< .05	.....	.40–.60		

* Some high-speed steels also contain 3 to 5 per cent of cobalt.

While commercial forms of iron and steel have in general several elements associated with the iron, and each of these has some effect on the physical properties, it is customary to consider the material as essentially an alloy of iron and carbon, the inherent properties of which are modified by the other associated elements.

657. Determinations of Constitution of Iron and Steel.—The pioneer attempts at grouping the iron-carbon series into a constitution diagram were made by Sauveur, in 1896, and Roberts-Austen, in 1897. In 1900, Roozeboom constructed a diagram based upon experimental data and interpreted in accordance with the "Phase Rule." The data were accurately redetermined and somewhat elaborated by Carpenter and Keeling, in 1904. Since that time many investigators have striven to determine the iron-iron carbide constitution diagram. Among the more recent diagrams are those presented by Honda, Daeves, and Epstein. Probably the best available at the present time is that proposed by Epstein in his book *Alloys of Iron and Carbon.*

658. Critical Temperatures.—Iron is a relatively complex element. Between its freezing point of 1535° C. and normal temperatures, it exhibits transition points at 1400°, 910°, and 770° C. which are indicative of the allotropic states of the iron. Iron exists in three allotropic states (four if beta iron is accepted), from room temperature up to the freezing point. Alpha iron existing below 910° C. has a body-centered cubic lattice, gamma iron existing between 910° to 1400° C. has a face-centered cubic lattice, while delta iron existing between 1400° and 1535° C. has a body-centered cubic lattice. It has been proved definitely by X-ray analyses that beta iron has the same crystal structure as alpha iron. There is, however, a slight break in the cooling curve at the critical temperature of 770° C. and a loss or gain of magnetism by the iron when heated above, or cooled below, that temperature. The question of the existence of beta iron hinges on the definition of allotropy. If this definition requires a change in the crystal structure, then beta iron does not exist; if only a reversible change in physical properties is required, then it does exist. The transition from alpha to gamma iron at 910° C. is accompanied by a change in the crystallographic form of the iron, which, in turn, affects the solubility relations of the iron and carbon, and, therefore, has a most vital bearing upon the structure and physical properties. The critical temperatures in the vicinity of 770° and 910° are called the A_2 and A_3 points, respectively. Owing to lag in reaction, they are somewhat higher on rising temperature than if recorded on cooling curves; the designations Ac_2 and Ac_3 are used for the former, and Ar_2 and Ar_3 for the latter. In the iron-carbon alloys there are two other important critical temperatures, A_0 at 210° and A_1 at 723° C. A_0 is important because it is the temperature at which there is a reversible magnetic transformation in the iron carbide; the importance of A_1 will be indicated in Art. 660.

659. Definitions.—Iron forms with carbon a compound having formula Fe_3C, technically classified as cementite, and often called iron carbide or combined carbon. It contains 6.67 per cent of carbon and 93.33 per cent of iron, and is extremely hard and brittle; in fact the hardest constituent of steels, about 6 to 6½ compared with 4 to 5 for iron in Mohs' scale.

In metallographic nomenclature the carbonless iron is called ferrite.

Carbon in the form of small flakes or thin plates, which are mechanically mixed with the iron, is called graphite.

Austenite is a solid solution of carbon in gamma iron. Maximum solubility of 1.7 per cent carbon occurs at 1130° C.

Pearlite is a mechanical mixture of ferrite and cementite containing 12.5 per cent cementite and 87.5 per cent ferrite.

660. The Iron-Iron Carbide Constitution Diagram.—For purposes of discussion it is best to consider the alloying relations between iron and cementite (Fe_3C) as the constituents of the binary series. For each 1 per cent of carbon there is 15 per cent of Fe_3C formed, and the limit of the series will be at 6.67 per cent carbon, or 100 per cent of the Fe_3C. A simplified constitution diagram is shown in Fig. 1. The melting-point of pure iron is taken as 1535° C.; that of cementite is not known, since it has not been isolated in mass, and it undergoes decomposition before fusion. It is not material to the discussion, however, since the useful range of composition does not exceed 5 per cent of carbon content.

In representing the simplified form of the constitution diagram the four omissions listed below have been made, none of which are believed to be of major importance in the discussion of ordinary iron-iron carbide alloys: 1, the A_0 line at 210° C.; 2, the region at eutectoid temperature and carbon less than 0.04 per cent, in which there is a slight solubility of carbon in alpha iron; 3, beta iron; 4, the peritectic region at 1400 to 1535° C.

Consider first only that part of the diagram above 1100° C. It is typical of complete solubility of iron and carbon in the liquid condition, with partial solubility in the solid, at least at the iron end of the series. Addition of either constituent to the other lowers the freezing-point of the alloy to a eutectic temperature and composition *E* of 1130° C. and 4.3 per cent carbon (64.5 per cent Fe_3C), respectively. The limit of solid solubility is at *S*, that is, 1.7 per cent of carbon, or 25 per cent of cementite, at 1130° C.; this solubility decreases, however, with further lowering of temperature as is indicated by the slope of the line *PS*.

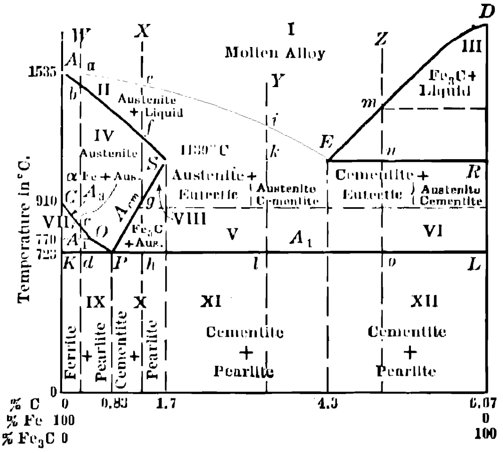


FIG. 1.—Modified Iron—Iron Carbide Constitution Diagram.

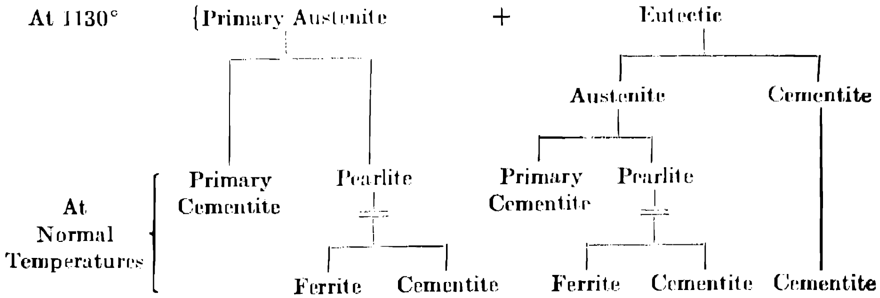
Consideration of the diagram below 1100° C. indicates a complexity resulting from the change in solubility relationships. At 1130° C. gamma iron will have a maximum of 1.7 per cent carbon in solution, while the maximum amount of carbon dissolved in alpha iron, at 723° C., is approximately 0.04 per cent (not shown in Fig. 1). The breaking down of the austenite, because of the changing solubility relationships, occurs in a manner analogous to that of a molten alloy whose solid solubility is nil. The slope of the line *GOP* indicates that the presence of carbon in solid solution lowers the transformation temperature of gamma iron to alpha iron. The slope of the line *SP* indicates that the solubility of carbon in gamma iron decreases as the temperature is decreased. The point *P*, called the eutectoid to distinguish it from the eutectic at *E*, occurs at a temperature of 723° C. and a carbon content of 0.83 per cent. The vertical line through *S* separates the steel region, 0 to 1.7 per cent carbon, and the cast-iron region, 1.7 to 6.67 per cent carbon.

661. Behavior of Typical Alloys in Cooling.—Examination of the iron-iron carbide constitution diagram shows that it can be broken up into three regions. The transformations in the cast-iron region, 1.7 to 6.67 per cent carbon, follow in a manner similar to those of Art. 628. The changes from the molten alloy to solid solution austenite, 0 to 1.7 per cent carbon, occur in manner similar to those which take place for any two materials soluble in both liquid and solid states (Art. 632). The transformations in the solid state for the steels from solid solution austenite to ferrite plus pearlite, or to cementite plus pearlite, are analogous to those which occur in two materials soluble in the liquid state but insoluble in the solid state (Art. 628). The changes which take place on cooling will be discussed for four typical alloys.

Discussion of changes on cooling for alloy *W*, Fig. 1, will be typical of all the hypoeutectoid steels (0 to 0.83 per cent carbon). As alloy *W* is cooled through the molten region no change takes place until the temperature *a* at the intersection with the liquidus *AE*. The first solid to form is austenite, with a carbon content that can be determined by drawing a horizontal line through *a* until it intersects the solidus *AS*. As the temperature falls, freezing continues, and both the solid austenite and the liquid become richer in carbon. Freezing will be complete when the temperature has dropped to *b*. The resultant solid, with a cooling rate slow enough to allow uniform diffusion, will be a homogeneous solid solution, austenite, containing the same amount of carbon as the liquid alloy *W*. The austenite suffers no change until the temperature drops to *c* at intersection with *GOP*. Here the precipitation of primary ferrite begins. As the temperature is decreased from *c* to *d*, more primary ferrite is precipitated, and the austenite consequently becomes richer in carbon, reaching finally the eutectoid composition *P* at 723° C. At 723° C. the austenite splits up into the eutectoid mixture of ferrite and cementite, which is called pearlite, but the primary ferrite remains unchanged. There is no further phase change with further cooling. The final alloy will have a heterogeneous structure consisting of primary ferrite plus pearlite (see Fig. 3*b*, 3*c*, 3*d*, and 3*e*). The proportion of pearlite to ferrite will depend on the carbon content of the alloy, reaching 100 per cent for a carbon content of 0.83 per cent. The final structure of the eutectoid alloy will be completely pearlitic, as is shown in Fig. 3*f* and 4*b*.

The changes on cooling of alloy X are typical of the hypereutectoid steels, 0.83 to 1.7 per cent carbon. Freezing begins at temperature e, with separation of austenite, and is completed at temperature f. The mechanism of solidification between e and f is similar to that discussed previously for alloy W. There is no change in the austenite as it cools from f to g. At g the first particle of primary Fe_3C is precipitated out of solution. As the temperature drops from g to 723° C., more primary Fe_3C is precipitated, and the austenite becomes poorer in carbon, reaching finally the eutectoid composition P. Again at 723° C. the residual austenite changes to pearlite, while the primary cementite undergoes no change. There is no phase change due to further cooling, and the final structure is heterogeneous, consisting of primary cementite plus pearlite (Fig. 3g). The proportion of primary cementite will increase and that of pearlite will decrease as the carbon is raised above 0.83 per cent.

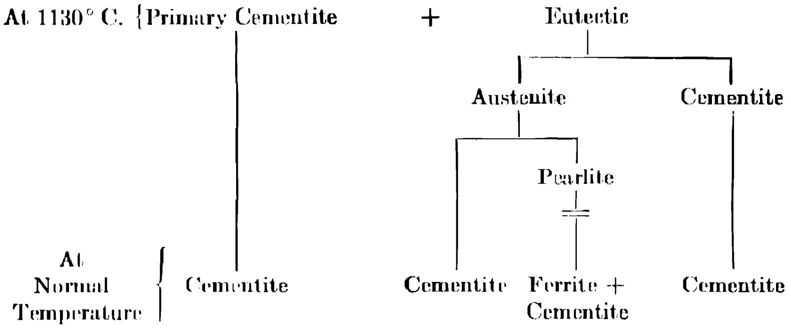
Iron-carbon alloys of more than 1.7 per cent carbon have a heterogeneous structure after solidification at 1130° C. Alloy Y typifies the hypoeutectic cast irons, containing from 1.7 to 4.3 per cent carbon. Solidification begins at i with separation of austenite from the liquid and is completed at k. Meanwhile the carbon content of the austenite increases to 1.7 per cent and that of the liquid increases to 4.3 per cent. At 1130° C. the primary saturated austenite remains unchanged, while the liquid solidifies to form the eutectic, a mixture of cementite and saturated austenite. As the temperature cools from 1130° C. down to 723° C., cementite is precipitated out of the primary austenite and also out of the austenite in the eutectic, leaving less carbon in solution, as is indicated by the line SP. At 723° C. the residual austenite has reached the eutectoid composition, and breaks down into pearlite. There is no further phase change down to room temperature. In outline form the alloys between 1.7 and 4.3 per cent undergo transitions as follows:



Thus at ordinary temperatures, two constituents only, the cementite and ferrite, are present; yet there is complexity of structure because the cementite may have five degrees of aggregation due to the selective separation, while the ferrite may have two—that in the pearlite from decomposed primary austenite and that in the eutectic.

An alloy of the eutectic composition of 4.3 per cent carbon will undergo transition in accordance with that part of the diagrammatic scheme above referring to the eutectic.

Hypereutectic cast irons, like *Z*, have a structure immediately after solidification of primary cementite plus a eutectic of saturated austenite and cementite. The proportion of this eutectic decreases with increase of carbon above 4.3 per cent. All of the cementite remains stable upon lowering the temperature to normal; the austenite, however, undergoes progressive transition, first by primary separation of cementite, and finally, at 723° C. by formation of pearlite. The diagrammatic representation is as follows:



The cementite may have four degrees of aggregation; the only ferrite is that found in the pearlite formed from transition of the austenite of the original eutectic.

662. The Formation of Graphite.—Silicon is always associated with the commercial alloys of iron and carbon. In steel the proportion of silicon is small and its influence is chiefly confined to the mitigation of structural defects; but in cast iron, where it is present in larger proportions, silicon exerts an influence both on the solubility of carbon in iron and on the stability of cementite in cooling.

With 1 to 3 per cent of silicon and slow cooling the percentages of carbon required for saturation and for the eutectic are less than for a pure carbon-iron alloy. Therefore, points *S* and *E* of the constitution diagram are shifted to the left by additions of silicon. In the alloys having more carbon than the eutectic, the cementite of region III is very unstable under the above-mentioned conditions and readily breaks up into graphite and ferrite while cooling through region VI. In alloys of less carbon than eutectic composition the cementite of region V decomposes quite easily. Cementite liberated by cooling austenite in regions V and VI breaks up less readily, and that in the pearlite of regions XI and XII is decomposed with difficulty. With the rate of cooling and carbon content constant, the proportion of graphite will vary with the percentage of silicon. If the silicon content and rate of cooling are constant graphitization will increase with the percentage of carbon. Again, if the composition remains constant more carbon will be freed by slow cooling than by rapid cooling.

Thus, depending on the proportion of silicon and the rate of cooling, a high-carbon alloy may have any one of the following constitutions:

1. Cementite plus pearlite;
2. Cementite plus pearlite plus graphite;
3. Pearlite plus graphite plus ferrite;
4. Graphite plus ferrite, which is the only stable constitution but is also very rare.

663. Structures in Iron Carbon Alloys.—Fig. 2 gives in diagrammatic form the structural relations of the iron-carbon series. For 0.3 per cent of carbon, the relative proportions of the constituents will be two-thirds excess ferrite and one-third pearlite; for 0.6 per cent carbon, one-third ferrite and two-thirds pearlite; for 0.83 per cent carbon, all pearlite. Above 0.83 per cent carbon, cementite becomes the excess constituent of primary separation. An alloy of 2.0 per cent carbon will consist of 20 per cent excess cementite and 80 per cent pearlite; while with 3.8 per cent of carbon, the structure will show one-half cementite and one-half pearlite. The pearlite is in all cases of constant composition, 87.5 per cent of ferrite and 12.5 per cent of cementite; and the total ferrite or cementite in the alloy will be that constituting the excess substance—either ferrite or cementite alone—plus the amount in the pearlite.

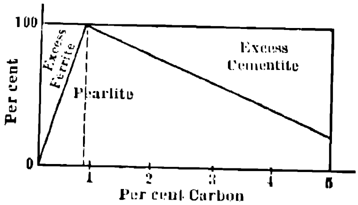
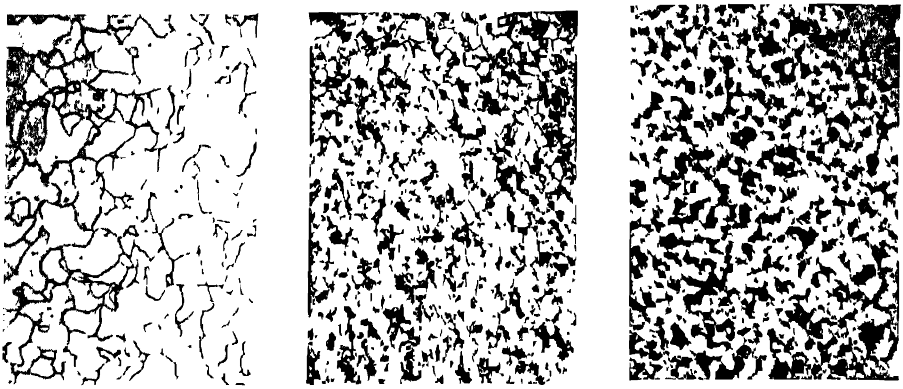


Fig. 2.

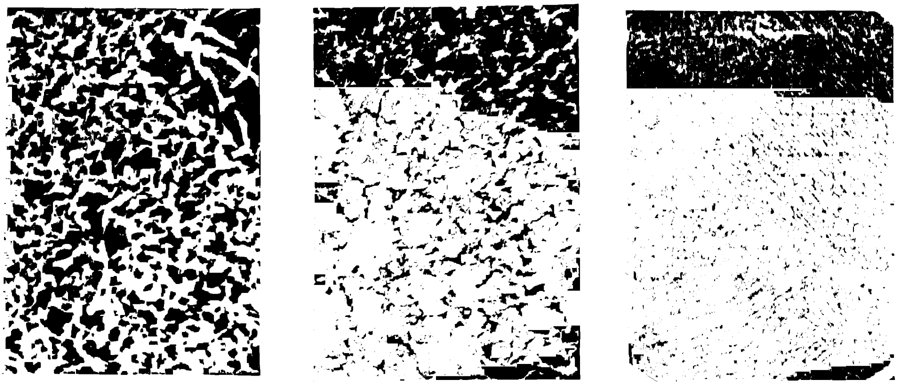
Typical microstructures of the iron-carbon series are given in Fig. 3 and 4. The etching has been with picric acid solution; this reagent does not attack cementite, and ferrite in mass but very slowly. Therefore, they retain the mirror-like reflecting surface of the polished specimen and appear white in the photographs. However, it does attack the ferrite of the pearlite, probably because of its fine state of division and the electrolytic action set up with the closely associated cementite. Consequently, since the ferrite constitutes 87.5 per cent of the pearlite, and the latter is usually in such a fine state of aggregation that under lower magnification (150 diameters or less) its separate constituents are



(a) Ingot Iron, C. = 0.00%.

(b) Steel, C. = 0.10%

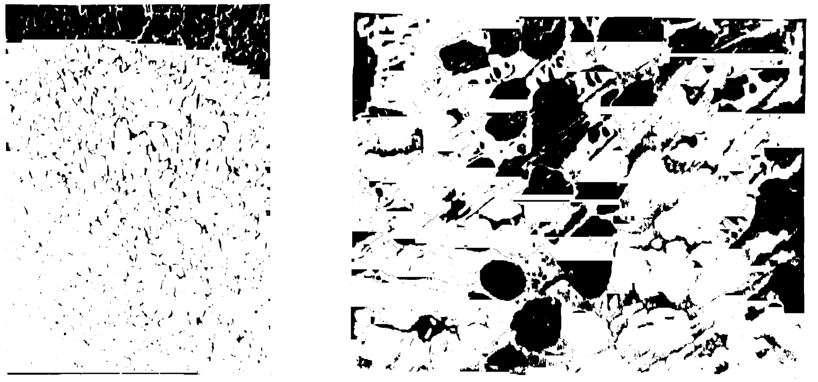
(c) Steel, C. = 0.27%



(d) Steel, C. = 0.45%.

(e) Steel, C. = 0.74%.

(f) Steel, C. = 0.85%.



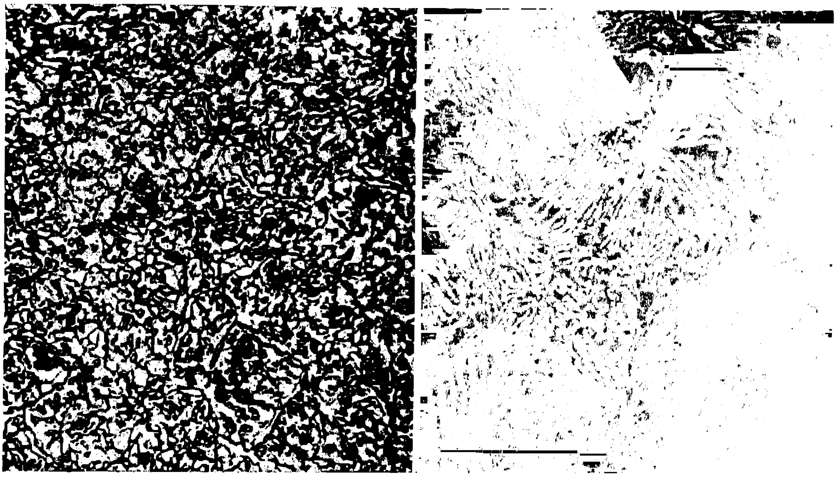
(g) Steel, C. = 1.5%.

(h) White Cast Iron, C. = 3.5%.

FIG. 3.—Structures of Iron-Carbon Alloys Slowly Cooled.

Black constituent in (b), (c), (d), (e), (g) and (h) is pearlite. White is ferrite in (b), (c), (d) and (e), cementite in (g) and (h). In (f) is shown lamellar pearlite, here the black is ferrite and the white cementite. Fig 3a by Ragatz, Fig 3f by Insley, others by Aston. Mag in f, 1000 d., in others, 70.

not revealed, the pearlite is apparently entirely etched, and then appears black in the photograph, due to the dispersion of the light by the roughened surface.



(a) Magnification = 110d. (b) Magnification = 1000d.

Fig. 4.—Globular Pearlite (a) and Lamellar Pearlite (b). (Courtesy of Sauveur an Boylston).

Higher magnifications (500 to 1500 diameters) reveal the composite nature of the pearlite, see globular pearlite in Fig. 4a and lamellar type in Fig. 4b. The black constituent is the ferrite and the white cementite.

CHAPTER XXII

PROPERTIES OF WROUGHT IRON

664. Structure.—Under the microscope wrought iron is seen to consist of grains of ferrite more or less surrounded by filaments of slag. In the cross-sectional view of Fig. 1*a* the slag inclusions appear as dark rounded patches of variable size, whereas in the longitudinal section, Fig. 1*b*, their thread-like nature is evident. The amount of slag in the iron depends upon the character of materials charged into the furnace, upon the work received by the puddle ball and upon the amount of hot work done in shaping the iron. The size of the ferrite grains is dependent upon the time the metal is held at temperatures above the critical range and upon the temperature from which it cools. High temperatures and long soaking periods favor large grains. Rapid cooling and continued hot working of the iron while it is above the recalescence point effect small grain size. To secure maximum fineness of grain the hot work should not cease until the temperature has fallen to about 700° C. The ductility and toughness of the iron are rendered high by removing the slag and by making the grain size as fine as possible without causing permanent distortion of the grains.

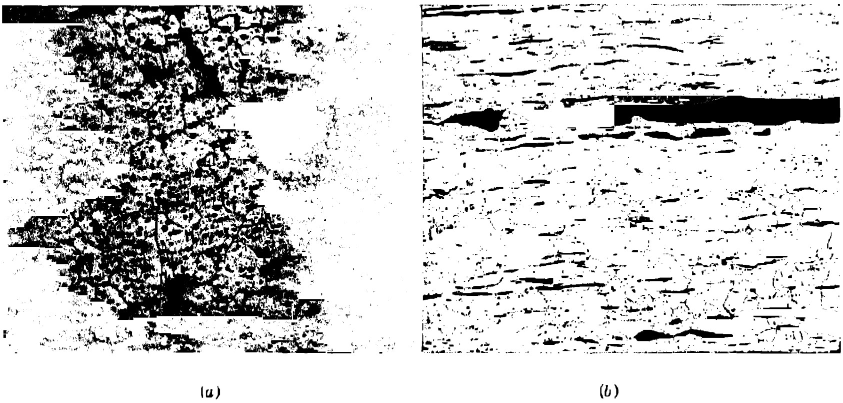

(*a*) (*b*)

FIG. 1.—Photomicrographs of Wrought Iron. (*a*) Section Transverse to Direction of Rolling; (*b*) Section Parallel to Rolling. (Courtesy of Sauveur and Boylston) Magnification, 50 Diameters.

When, however, a wrought-iron bar of uniform section is ruptured in the ordinary tensile test it generally exhibits an irregular fibrous fracture (Fig. 6, Ch. III). Occasionally, if the iron has been made from steel scrap or if it has not been properly worked during the "boil," the tension fracture will be partially or wholly crystalline. On the other hand if wrought iron fails under shock or under repeated loading it generally has a crystalline fracture. This circumstance has led some to the erroneous conclusion that the iron crystallizes in service due to vibrations or shock. As a matter of fact the structures of all ferrous metals are crystalline. Other indications sensed by the naked eye are due to the drawing out of the grains by the method of testing to such extent that they are no longer visible as such but appear like fibers,—or, in soft steel, like fine silk. Thus, good wrought iron normally presents a distinct fibrous fracture in tension due to the presence of the brittle slag filaments which imperfectly surround groups of iron grains. The latter are drawn out in the test, but the slag filaments, being more brittle than the ferrite, cause minute planes of discontinuity which by contrast make the bundles of iron grains appear like fibers. In soft steel where no slag is present there is no grouping of iron grains; the structure is more homogeneous, and the fracture, being much finer and more uniform in texture, appears silky.

The occasional crystalline fracture of wrought iron under static tension is generally due to the presence of particles of steel or cast iron in the path of the break. These particles on rupturing exhibit their normal structure.

The crystalline fracture under shock is due to the suddenness of the application of the force, time not being given for more than partial distribution of the induced stresses to adjoining sections or for drawing out of the grains at the break.

When a bar of wrought iron containing considerable steel scrap is nicked with a chisel or grooved with a tool and broken transversely, it is likely to show a crystalline or partially crystalline fracture, although in tension the fracture may be fibrous. The crystalline fracture is due to the stress concentration at the root of the nick and the reinforcement afforded by the sides of the nick. This condition causes a large stress to be exerted on a comparatively few grains without allowing elongation, and a break squarely across the grains ensues. The scrap steel portions of the bar containing little slag will, when fractured, appear crystalline.

The crystalline failure under repeated stress is readily accounted for by the formation of slip bands, as explained in Art. 832.

665. Defects.—The evil influences of phosphorus and sulphur appear to be less pronounced in wrought iron than in steel. This may be due to the fact that there is less opportunity for segregation in the puddling process than in processes where the metal is cast from a molten state. Furthermore, much of the impurities in wrought iron are affiliated with the slag rather than the iron. However, a very high sulphur content (0.3 to 0.5 per cent) is likely to cause the iron to crumble, or exhibit what is known as red shortness, in forging or welding. Sections rolled from *red short* iron are likely to have rough edges. A phosphorus content of 0.4 to 0.5 per cent, if the phosphide surrounds the ferrite grains, causes the iron to be brittle at cold temperatures (*cold short*) and renders it hard and coarsely crystalline. Such iron cannot be refined by heat treatment.

In sheets or plates spongy spots, often called *spilly places*, are occasionally found. These defects are due to burning of portions of the iron in puddling. *Blisters* are also found on plates and sheets made of inferior iron. They appear to be due to the oxidation of carbon in the iron by the oxide of iron in the slag.

666. The tensile strength of wrought iron along the grain is practically the same as the tenacity of ferrite, and varies from 45,000 to 55,000 lb. per square inch. It is greater in small rods and thin plates than in large bars and thick sections, the material remaining the same. This is shown in Fig. 2, where the same material has been rolled into bars from ⅜ in. to 2 in. in diameter, the tensile strength varying from 52,000 in the smaller to 47,500 lb. per square inch in the larger sizes. The increase in strength is probably due to the reduction in the size of the ferrite grains which is favored by a large amount of hot work and is attended by an increase in density and cohesion between grains.

The Elastic Limit is more dependent on the thinness of the final section than is the tensile strength, as is well brought out in Fig. 2. Here the apparent elastic limit varies from 40,000 lb. per square inch in the ⅜-in. rods to 23,000 lb. per square inch in the 2-in. rods, and is almost identical with the "yield-point." This increase in the elastic limit with increased reduction in the rolls always occurs with wrought iron and steel, but it is much more pronounced with wrought iron. The true elastic limit of wrought iron is nearly always much lower than the apparent elastic limit. In Fig. 2 it is found from 5000 to 7000 lb. lower in every case. In mild steel these two limits are almost identical.

The Percentage of Elongation in 8 in. varies from 5 per cent to 25 per cent when tested in the direction of the fibers, depending on the quality of the material, the reduction of area averaging about 50 per cent more than the elongation. The elongations recorded in Fig. 2 were all taken on a length of 20 in., which somewhat reduces the percentage, especially for smaller sections. Iron with high slag content will exhibit less elongation and far less reduction in area than the best grades of Swedish iron which run low in slag.

The pulling speed appears to have little effect on the strength or ductility of wrought iron when the test-pieces are of standard dimensions. In *Tests of Metals*, 1887, p. 924, there are data to show that high speeds, say 5 in. per minute, will raise the strength of grooved specimens 4 per cent and the strength of specimens with short gage lengths, about 2 per cent above the values for very slow speeds. The ductility of such specimens is decreased by rapid application of stress.

667. The tensile strength across the grain is always much less than along the grain for wrought iron, whereas with steel there is no appreciable difference. From Bauschinger's *Communications*, Vol. 2, the following data were gotten.

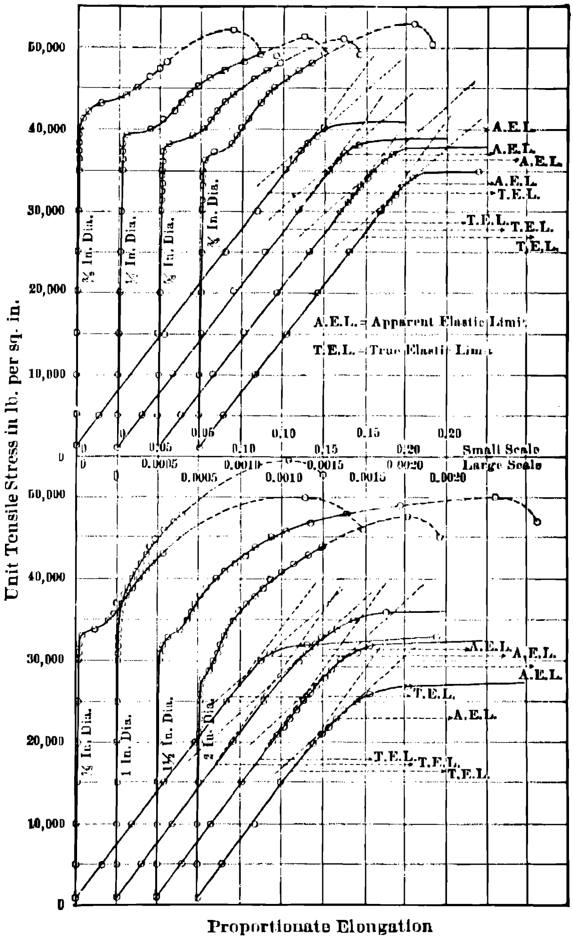


FIG. 2.—Stress-diagrams (in Tension) of Wrought-iron Bars of Varying Diameters, all Rolled from the Same Material. All elongations measured on a length of 20 in. The "Apparent Elastic Limit" falls from 2% to 10% lower than the indicated "Elastic Limit" in the original report; it varies from 23,000 in the 2-in. to 40,000 lb. in the ⅜-in. specimens; and it marks a point where the permanent set is less than 0.0001 of the length of the specimen. Each diagram is the average of from 3 to 6 tests. (*Tests of Metals*, 1888.)

The ratio of lateral to longitudinal tensile strength from eight tests in each direction on iron of an exploded boiler was 0.74. From the same number of like tests on iron of a second boiler the mean ratio 0.71 was computed. Results of tests on six new plates from as many different sources yielded ratios of 0.76, 0.62, 0.92, 0.90, 0.76 and 0.83.

It is asserted that by cross piling of the "puddled lumps" (small slabs corresponding to muck bar) the best Lowmoor iron plate of Yorkshire, England, is given an ultimate strength parallel to the rolling of 51,500 lb. per square inch and elongation of 16 per cent. Across the grain the strength is 45,000 lb. per square inch and the elongation 12 per cent. This material is about four times as costly as the best of steel plates consequently its use for purposes where forging and welding are not required is declining.

In conclusion we may say that the tensile strength of wrought iron transverse to the direction of the rolling ranges from 60 to 85 per cent of its strength parallel to this direction.

668. The compressive strength of wrought iron, like that of other ductile metals, must be regarded as the yield point. At this stress the metal buckles out of shape; and, if the specimen has appreciable length, failure follows. It is likely that thin sections which receive more work during rolling will be stronger than thick sections. Assuming the yield points of wrought iron in tension and compression to be the same, we see from Fig. 2 that the ultimate strength in compression of short sections $\frac{1}{4}$ to $\frac{5}{8}$ in. in thickness will vary from 40,000 to 30,000 lb. per square inch. Since the elastic limit of thin steel sections is not increased so much by reduction in rolling, it becomes apparent why many of the wrought-iron columns built of very thin material have, when tested, exhibited ultimate strengths nearly as great as columns of mild steel.

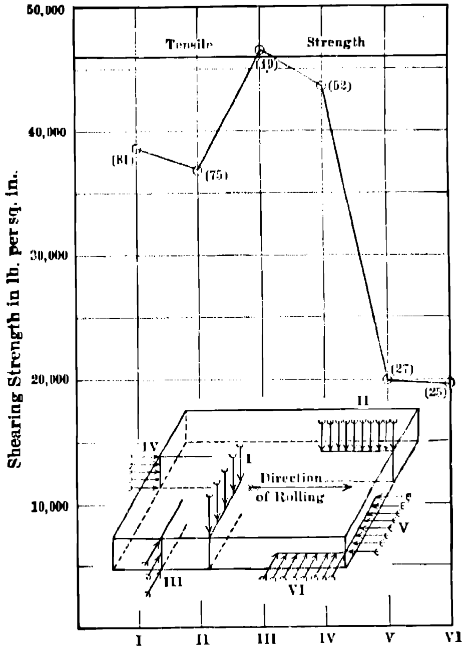


FIG. 3.—The Shearing Strength of Wrought Iron on the Six Principal Planes, as Compared with its Tensile Strength. Figures indicate the number of results averaged. (*Bauschinger's Communications*, Vol. II).

669. The Shearing Strength of Wrought Iron.—A very elaborate investigation of the properties of wrought iron was reported by Bauschinger in his *Communications*, Vol. 2. He made several hundred shearing tests on wrought-iron plate from seven different sources and found the shearing strengths in two directions on each of three principal planes as shown in Fig. 3. Since there was a general agreement in the relative strength on these planes, only the averages for a portion of the tests are given in the diagram. In general, we may say that the shearing strength across the thickness of the plate, either with or across the grain, is about 80 per cent of the tensile strength, while if the external forces are parallel to the plane of the plate, and are applied on the planes perpendicular to the plane of the plate, the shearing strength is about the same as the tensile strength. The shearing resistance on a plane parallel to the plane of the plate is less than 45 per cent of the tensile strength.

670. The modulus of elasticity of wrought iron lies between 25,000,000 and 29,000,000 lb. per square inch for either tension or compression. Iron of good quality usually has a modulus of approximately 27,000,000 lb. per square inch. Values reported by C. A. Marshall in *Trans. Am. Soc. Civ. Engr.*, Vol. 17, p. 62, are given in Table 1.

TABLE 1.—VALUES OF THE MODULUS OF ELASTICITY OF WROUGHT IRON

(IN 1000 POUNDS PER SQUARE INCH)

Size of Bar.	TENSION.		COMPRESSION.		Size of Bar.	TENSION.		COMPRESSION.	
	E_1 First Loading.	E_2 Second Loading.	E_1 First Loading.	E_2 Second Loading.		E_1 First Loading.	E_2 Second Loading.	E_1 First Loading.	E_2 Second Loading.
$\frac{3}{4}$ rd.	26,800	27,500	25,840	26,160	1 sq.	28,290	28,290	27,100	27,990
$\frac{3}{4}$ rd.	26,980	27,410	25,920	26,240	1 rd.	27,590	28,570	27,250	28,570
1 rd.	.....	26,700	25,670	26,440	1 rd.	28,290	28,480	27,430	28,570
1 rd.	27,540	27,540	26,020	26,350	1 rd.	26,580	28,480	26,500	28,180
$\frac{3}{4}$ sq.	28,990	.....	27,420	.....	$\frac{7}{8}$ rd.	30,190	30,190	29,520	29,910
$\frac{3}{4}$ sq.	27,790	29,180	25,650	27,790					
1 sq.	27,800	27,900	26,490	27,300	mean	27,894	28,203	26,734	27,590

They indicate that the modulus is slightly greater after the specimen has been strained than on first loading. The modulus of elasticity in torsion is approximately 11,600,000 lb. per square inch.

671. Effects of Overstrain.—As in steel and other ductile metals so in wrought iron, when strained beyond its elastic limit and allowed to rest the elastic limit and ultimate strength are raised but the elasticity under stress of opposite kind is impaired. Fig. 4 shows the effects of overstressing three 3-in. × 1-in. wrought-iron bars. The original bars were 100 in. long between gage points. They broke at an average ultimate strength of 53,200 lb. per square inch with an elongation of 16 per cent in 100 in. The second tests were made on the broken halves using a 50-in. gage length. It will be noted that after several months rest the elastic limit, computed on the original area, is higher than the initial ultimate strength of the second test. The elongation has, however, been markedly reduced. Annealing of the overstressed pieces reduced the elastic limit and ultimate strength below the original values. Stretching the iron slightly beyond the elastic limit

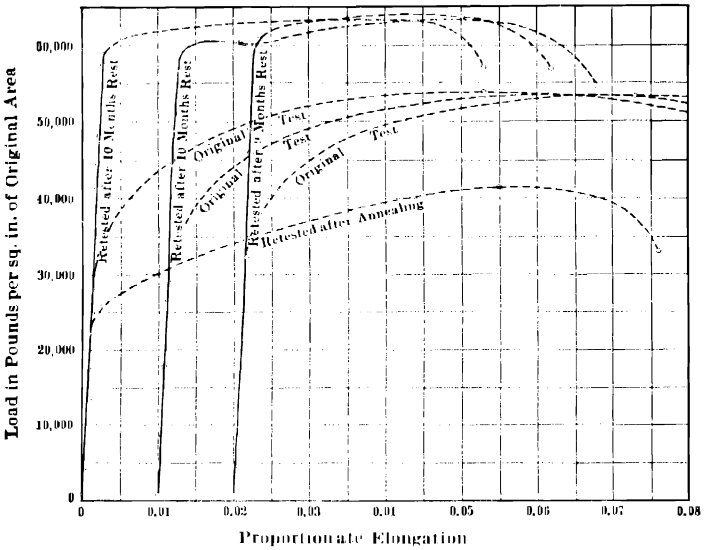


FIG. 4.—Wrought Iron Bars, 3 by 1 by 100 In., Retested. First test gave $S_e = 30,000$ lb. per in.²; $S_t = 53,700$ lb. per in.²; per cent elong. in 100 in. = 16. retests were made on the ends of the broken bars. Elongations were measured in 50 in. and unit stresses were computed in terms of original areas. (*Tests of Metals*, 1882.)

would cause less marked changes in strength and ductility. Fig. 5 shows that the magnitude of the effect of overstrain is dependent to some extent upon the subsequent period of rest.

Fig. 6 illustrates the loss of elasticity suffered by wrought iron due to reversal of stress immediately after overstrain. In the first test the specimen was given a permanent elongation of about 1 per cent. After release of the tensile load it was subjected to compression, but showed a loss of elasticity as seen in the stress-diagram. When compressed to its original length and reloaded in tension it showed loss of elasticity in tension. After being again overstrained in tension about

1 per cent it once more became elastic, but lost its elasticity when elongated 18 per cent and reloaded in compression. Similar results for steel also are reported in *Tests of Metals*, 1899.

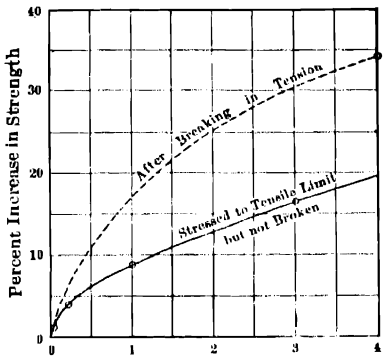


Fig. 5.—Increase in the Tensile Strength of Wrought Iron after having been Stressed to the Tensile Limit and Allowed to Rest. Points represent 5 to 15 results each. (*Report U. S. Test Board*, 1881, Vol. I, p. 111 and 115).

672. The toughness of wrought iron under repeated shocks has lead many engineers to specify it in preference to soft steel for certain types of shafting. It is also claimed that wrought-iron studs for cylinder heads are tougher than those made of steel and that wrought-iron pipe buckles less often than steel in driving. Whatever evidence there may be of the superiority of individual parts, it does not seem fair, in view of variations in the qualities of both of the materials, to make such claims for class superiority. Experimental evidence seems to show that soft steel of good quality has more capacity for absorbing the energy of a single blow. On the other hand, basing judgment upon results of impact tests on slotted bars, it appears that good wrought iron when overstrained retains as high resistance to impact as soft steel similarly overstrained.

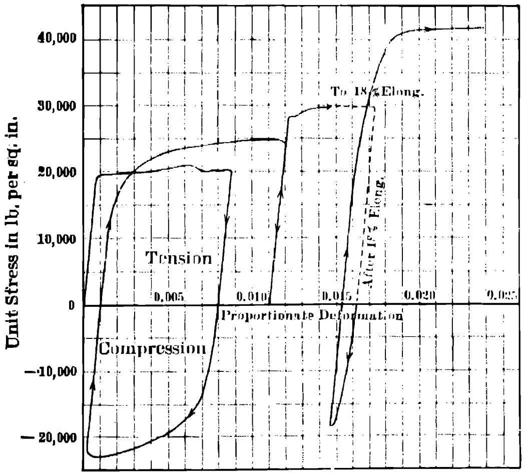


Fig. 6.—Showing that a Small Permanent Set in Wrought Iron either in Tension or Compression Greatly Reduces the Elastic Limit in the Opposite Stress, when that Stress is Immediately Applied. (Gray, in *The Digest of Physical Tests*, Vol. 1, p. 232, 1896.)

673. The Strength of Wrought-iron Chains.—The hundreds of tests on wrought-iron chains given in the *Report of the U. S. Test Board*, 1881, Vol. 1, show that the ultimate strength of chains may be taken at 1.6 that of the iron from which the links are made. It also appears from these tests that open links are somewhat stronger than studded links, though the open-link chains take a permanent set earlier than the studded links. It is thought, however, that open-link cables would foul more readily than the studded cables. The elastic properties of open-link chains made of 1-in. and $\frac{7}{8}$-in. iron are shown in Fig. 7, where the tests have been carried to the proof-load only, this being such as to give to the chains a permanent set of about 2 per cent of their length. They now become perfectly elastic to 20,000 and 15,000 lb. respectively, and are also about five times stiffer, or more rigid, than they were at first. All chains are improved by this treatment, while it also discovers any very poor welds the chain may have.

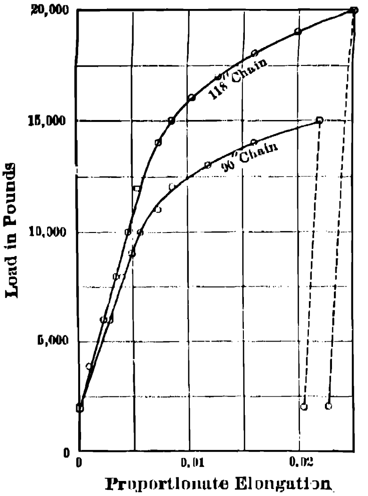


FIG. 7.—Proof Tests of Wrought-iron Chains with Open Links. The 118-in. chain was made of 1-in. iron, the 90-in. chain of $\frac{7}{8}$-in iron. (*Tests of Metals*, 1894.)

From theoretical analyses and from experiments on both open and stud links, Goodenough and Moore* have arrived at the following approximate formulas for maximum stresses in chain links:

for open links,
$$S_t = \frac{2P}{A},$$

for stud links,
$$S_t = \frac{1.6P}{A},$$

where S_t is the maximum unit tensile stress, P the load on the chain, and A the area of the stock. For either of the above chains the compressive stress on the inner fibers at the link ends is approximately double the maximum tensile stress. However, since the length of link under compression is very short and since additional security is affected at these points by the pinching action of the adjoining links, it appears practical to base the design upon the tensile strength of the link If 15,000 lb. per square inch is considered a safe value for tensile stress in chains, then the above formulas reduce to $P = 6000\ d^2$ for open links and $P = 7500\ d^2$ for stud links, where d is the diameter of the iron.

674. The Welding of Wrought Iron.—One of the most valuable properties of wrought iron is the facility with which portions of it may be united by squeezing or hammering while at a high heat. This characteristic renders the iron very useful to the smith. The property is due to the high plasticity of the iron throughout a considerable range of temperature extending below a white heat. However, if the iron parts are heated to such temperatures in the presence of much air their surfaces soon become coated with a film of iron oxide. Consequently it is difficult to bring the welding surfaces into perfect contact. To avoid imperfect cohesion it is necessary that the central portions of the surfaces in the weld be first brought together so that the oxide forming at the joint may be expelled outward and not entrapped as the seam is closed under the hammer. The evil effects of the oxide may be greatly reduced by using borax or other flux which acts as a solvent of the oxide and renders it more easy to expel from the joint. Moreover, by maintaining a thick fire in which most of the oxygen is combined with carbon, or by heating the parts in a muffle it is possible to considerably reduce the amount of slag formed. One of the advantages of electric welding lies in the fact that no air blast is employed, and by having the parts in contact during the heating period, air is largely excluded from the welding surfaces and hence little oxide is there formed.

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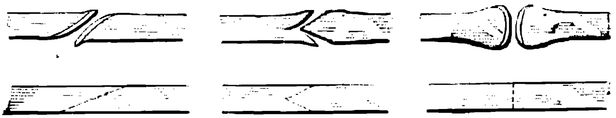
* *Bull.* No. 18, Engr. Expt. Sta., Univ. of Ill.



Lap Weld Cleft Weld Butt Weld

Fig. 8.—Common Types of Welds.

Fig. 8 shows the common types of welds and the shapes of the parts prior to welding. After the parts have been shaped and upset as required by the work in hand, they are reheated, if necessary, and then rapidly hammered until the metal is below a red heat. This hot work reduces the grain size and renders the metal at the weld more ductile and tough. Inasmuch as there is likely to be overheated metal on either side of the joint which has not been properly worked during the welding, it is best, wherever possible, to anneal welds and thus secure uniformity in structure and properties of the metal in the vicinity of the joint.

On account of the difficulties encountered in welding, the strength of welded joints is likely to vary from 30 to 100 per cent of the strength of the parts joined. With the most careful hand welding Kirkaldy reports the following average efficiencies: For the strengths of joints in round tie-rods 1½ to 3⅛ in. in diameter 60 per cent; for flat plates 2½ to 6-in. wide and ¼ to 1-in. thick 71 per cent; for chain-link welds on ½- to 2½-in. iron 216 tests gave an average efficiency of 83 per cent.*

Carefully conducted tests by Bauschinger showed an average efficiency of 95.6 per cent for wrought-iron and 89.2 per cent for soft-steel joints. Hand-forged welds of wrought iron gave an average efficiency of 87.9 per cent; those forged by steam hammer had an average efficiency of 91 per cent. With soft steel the hand-forged welds had an average efficiency of 84 per cent, while the power-forged welds developed an average efficiency of 97.2 per cent. The efficiency of the steel welds varied much more than those of wrought iron. These tests represent what can be done under best conditions in welding bars which vary in size up to 3¼ by 1.2 in. in cross-section.

Tests at the University of Illinois † on low-carbon steel welded by an oxyacetylene torch indicate that the efficiency of the material in the joints under static tension will average about 75 per cent when the work is done by a skilled operator. By slightly building up metal around the welds it is possible to make the strength of the joint equal to the strength of the solid section. Under impact the efficiency of oxyacetylene welds was about 50 per cent.

675. Methods of Distinguishing Wrought Iron from Soft Steel.— Often the mechanical properties as revealed by the tension test are ample to differentiate steel from wrought iron. Generally wrought iron exhibits lower elastic limit, ultimate strength and elongation than steel and a very much less reduction in area. The fracture is jagged and fibrous whereas steel is cup-cone and finely crystalline, or silky. The nick-bend test (Art. 144) serves as a determinator if the iron has a pronounced fibrous fracture. Compression tests on short prisms of wrought iron and steel generally furnish indications (Fig. 11, Ch. III).

Resistance to corrosion is another basis of distinguishing between these metals. The ends of small rods are turned or filed smooth and suspended for about a half hour in a solution of one part hydrochloric acid, three parts sulphuric acid and nine parts water. After immersion steel will be found to have been evenly attacked, whereas wrought iron specimens show ridges parallel to the axis of the specimen. The ridges are slag filaments which resist the attack of the acid much better than the intervening grains of iron.

The manganese content of wrought iron is usually less than 0.05 per cent whereas for steel it is above 0.30 per cent. Hence a chemical analysis furnishes a means of identification. Of all methods, the detection of slag filaments by the microscope is the most positive means of identification of wrought iron.

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* Kirkaldy's *System of Mechanical Testing*, London, 1891, Report K.K.

† *Bulletin* No. 45 and 98, Eng. Expt. Sta. University of Illinois.

CHAPTER XXIII

PROPERTIES OF STEEL

676. The principal factors influencing the properties of steel are: (1) chemical composition, (2) heat treatment, and (3) mechanical work. Composition bears a vital relation to the constitution of the metal and through structure has a most important bearing on physical properties. Heat treatment may be influential, (*a*) in altering the solubility relations of the constituents, (*b*) in changing the crystallization either with respect to form or degree of aggregation, (*c*) in introducing or relieving internal stresses in the metal. Mechanical work may be hot or cold; it has an effect (*a*) in altering the form of the crystalline aggregate, (*b*) in introducing internal stresses. We shall now consider the effects of these main factors together with certain other influences on the physical and mechanical properties of steel. Although for the sake of simplicity, we study these influences separately; yet we must continually bear in mind that combinations of all of them will, in general, affect the properties of a given piece of steel.

COMPOSITION

CARBON

677. Importance of Carbon in Steel.—We have already noted in studying the constitution of the iron-carbon alloys how very marked are the changes in structure which are produced by adding small percentages of carbon to pure iron. Indeed it is the presence of these small quantities of carbon which make it possible to secure the high degrees of hardness and strength that differentiate steel from ingot iron or wrought iron. On the other hand, the addition of carbon to iron decreases the malleability and ductility of the metal, and reduces its permeability to magnetic forces. If we refer to the constitution diagram, Art. 660, it will be noted that for a carbon content above 1.7 per cent there is always a heterogeneity of structure with separation of cementite, at temperatures below 1130° C., or completion of solidification. On the other hand, with a carbon content below 1.7 per cent, it is possible to have all of the carbon or cementite in solid solution in the iron, at some temperature below fusion. This limit of solid solubility at 1.7 per cent of carbon marks the theoretical dividing line between the steel and cast iron; the latter being non-malleable at any range of temperature.

678. The Physical Characteristics of Ferrite and Cementite.—Again referring to regions IX to XII of the constitution diagram we note that slowly cooled steels and cast iron consist of pure iron (ferrite) and iron carbide (cementite), a portion or all of the ferrite and cementite always being intimately associated in the eutectoid, pearlite. Ferrite is a relatively soft, ductile and malleable metal of low elastic ratio. Cementite, on the contrary, is extremely hard, brittle, non-malleable at any temperature, and has a high elastic limit equaling its tensile strength. It is to be expected, therefore, that the relative properties of these two constituents, together with the nature of the association and degree of aggregation, will determine the physical properties of steels and cast irons. In fact the strengths of normal carbon steels of less than eutectoid composition are in direct ratio to the percentage of pearlite, whereas in the hypereutectoid steels the strengths diminish slightly as the excess cementite increases.

679. The essential relations between carbon content and mechanical properties for the carbon-iron alloys containing 4 per cent or less of carbon are shown **in Fig. 1.** From the figure it will be observed that

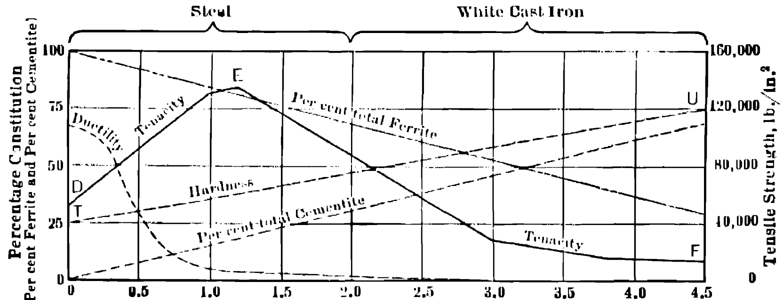

Fig. 1.—Theoretical Relations between Mechanical Properties and Carbon Content in Iron-Carbon Alloys. (Howe.)

the tensile strength increases to a maximum when the metal is approximately of eutectoid composition. This is probably due to the relatively intimate mixture and fine state of aggregation of the constituents of the pearlite. With a decrease or increase of carbon the ferrite or cementite, respectively, becomes an excess substance forming a grain network which has a weakening influence on the metal.

The relation of hardness to carbon content is dependent upon the kind of hardness. In Fig. 1 hardness is shown as varying directly with the increase in cementite. As measured by the Brinell ball method the resistance to indentation increases much more rapidly for carbon contents up to the eutectoid ratio (0.83 per cent C.) than for the higher percentages. Thus the Brinell number for soft iron lies between 75 and 80, for eutectoid steel it is approximately 250, and for

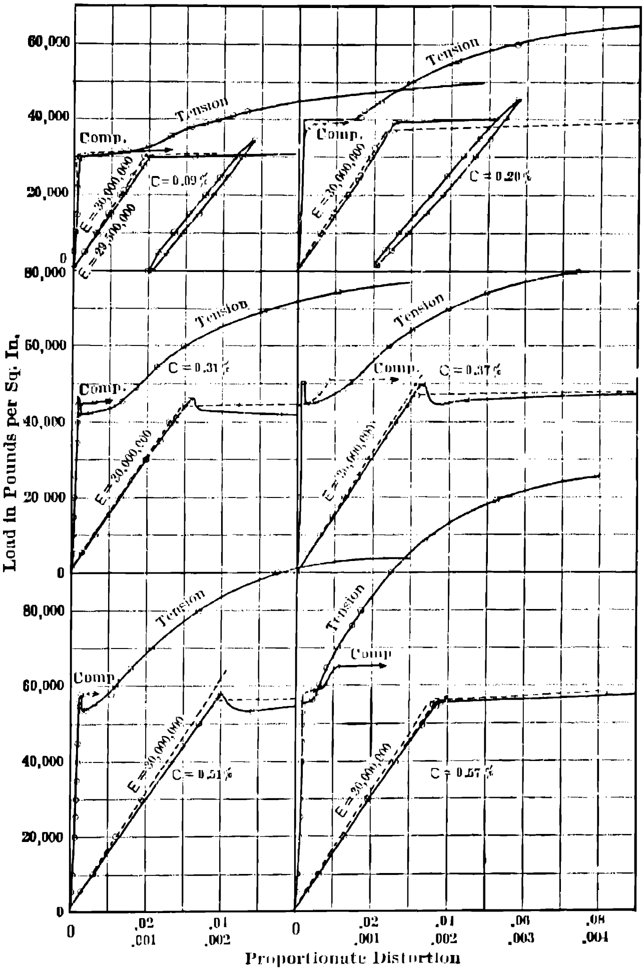

FIG. 2.—Compression and Tension Stress-diagrams of Steel Bars of Varying Percentages of Carbon.

Compression specimens 12 in. long and 1 in. in diam. $\left(\frac{l}{r}=33\right)$ with flat ends. Tension specimens same diam. with a gauged length of 30 in. All specimens turned from open-hearth steel bars $1\frac{1}{4}$ in. in diam. (*Tests of Metals*, 1886 and 1887.)

white cast iron it ranges from 350 to 500. Brinell's tests on carbon steels (Fig. 21) show that mean rate of increase in ball hardness is 19 (Brinell scale) per 0.10 per cent increase in carbon until the carbon reaches 1.0 per cent. Again from tests with various abrasive powders

F. Robin found that the wearing resistance of annealed or normal carbon steels was greatest when the carbon content was about 0.40 per cent. It is apparent, therefore, that the relation of hardness to carbon content varies greatly for different kinds of hardness.

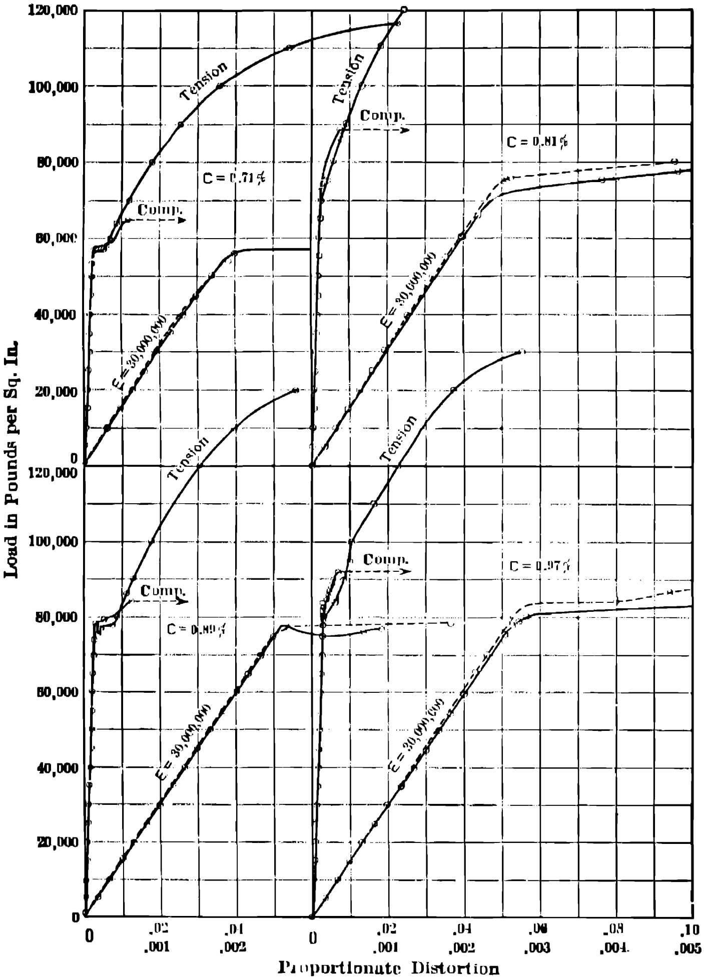

FIG. 3.—Supplementary to Fig. 2.

680. Influence of Carbon on Strength of Steel.—A study of the data shown in Fig. 2 to 5 indicates that the tensile strength of hot rolled steel bars varies from 55,000 lb. per square inch for 0.1 per cent carbon to 150,000 lb. per square inch for 1.0 per cent carbon. The strength of the hot rolled bars, Fig. 4, is a maximum between 1.0 and

1.2 per cent carbon; whereas, among the annealed bars, Fig. 5, those of eutectoid composition are the strongest.

If the strength given in Figs. 2 and 3 are also plotted on Fig. 4 it will be found that there is approximately a linear relation between the tensile strength (S_t) and the per cent carbon (C) for carbon content less than 1.00 per cent. This relation may be expressed by

$$S_t = 45{,}000 + 115{,}000\,C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

For annealed steels with low content of impurities Sauveur * proposes the following simple formulas:

$$S_t = 50{,}000 + 90{,}000\,C \ (C < 0.83 \text{ per cent}) \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

$$S_t = 142{,}000 - 20{,}600\,C \ (C > 0.83 \text{ per cent}) \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

Chemical Analyses											
Carbon, Per cent	0.140	0.180	0.320	0.460	0.490	0.570	0.710	0.820	1.010	1.220	1.390
Manganese, "	0.450	0.560	0.510	0.400	0.500	0.650	0.670	0.550	0.390	0.340	0.200
Sulphur, "	0.035	0.013	0.027	0.050	0.028	0.028	0.035	0.028	0.029	0.031	0.029
Phosphorus, "	0.018	0.024	0.009	0.020	0.013	0.012	0.027	0.018	0.016	0.025	0.015
Silicon, "	0.131	0.132	0.128	0.111	0.127	0.167	0.147	0.152	0.160	0.181	0.191

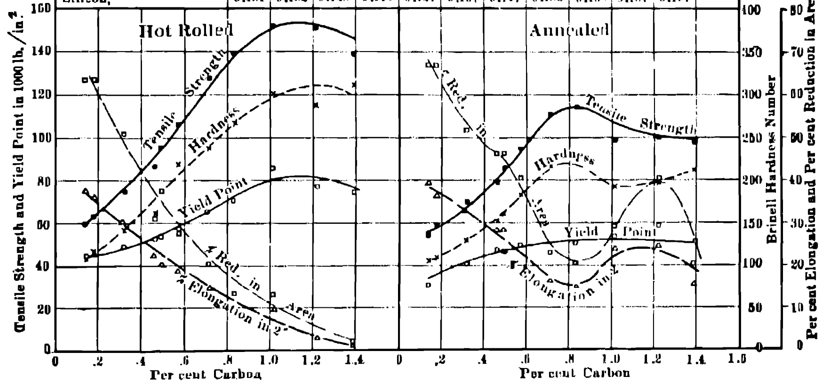

FIG. 4. FIG. 5.

FIG. 4.—The Influence of Carbon on the Mechanical Properties of Hot-Rolled Steels. (Nead.) Diameter of specimens 0.505 in.; gage length = 2 in.

FIG. 5.—The Influence of Carbon on the Mechanical Properties of Annealed Steels (Nead). Annealing temperatures were those recommended by A.S.T.M., which were slightly higher than those shown in Fig. 10.

Formula 3 gives results about 10,000 lb. per square inch higher than the data for annealed steels in Fig. 5.

From an extensive series of tests on acid and basic open-hearth steels Campbell † derived the following more complex formulas for the tensile strength (S_t) of steel.

For acid open-hearth steel, $S_t = 40{,}000 + 1000C + 1000P + x\text{Mn} + R$ . . . (4)

For basic open-hearth steel, $S_t = 41{,}500 + 770C + 1000P + yMn + R$ . . . (5)

In these equations *C*, *P*, and *Mn* represent the number of points ‡ of carbon (by combus-

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* *The Metallography and Heat Treatment of Iron and Steel*, p. 138.

† *The Manufacture and Properties of Iron and Steel*, p. 391.

‡ A point is equivalent to 0.01 per cent.

tion), phosphorus, and manganese, respectively, and R is a variable depending on the heat treatment. For rolled steels finished at the ordinary temperatures $R = 0$. If carbon is determined by the color method the coefficients for C in Eq. (4) and (5) should be 1140 and 820, respectively. Values of the coefficient x, for manganese over 40 points and carbon under 60 points, are given by $x = 8C$; values of y, for manganese over 30 points and carbon under 40 points, are given by $y = 4C + 90$, where C is the number of points carbon as before.

The *elastic limit* and the yield point of steel in tension, like the ultimate strength, increase with the carbon content but at a lower rate. The elastic ratio usually runs between 0.60 and 0.70 for the medium- and low-carbon steels and between 0.50 and 0.60 for the high-carbon varieties. Thus from the results in Figs. 2, 3 and 4, the following approximate relation $S_y = 30{,}000 + 48{,}000\, C$ is obtained. Here S_y is the unit stress at yield point and C the per cent carbon (< 1).

The yield point in high-carbon steels is much less pronounced than in low- or medium-carbon steels as the diagrams of Figs. 2, 3 and 9, indicate.

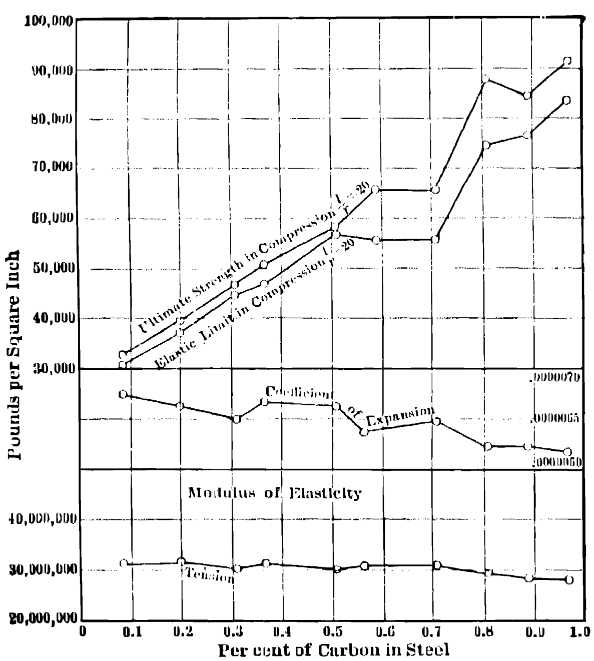

FIG. 6.—Variation of Compressive Strength, Coefficient of Expansion and Modulus of Elasticity with Carbon Content. (*Tests of Metals*, 1886.)

The *ultimate compressive strength* of steel in very short prisms is not well defined. In members with $\frac{l}{r}$ above 100, column action (Art. 21) is introduced, but in fairly short prisms with $\frac{l}{r}$ between 20 and 50 the compressive strength is practically equal to the apparent elastic limit, see Figs. 2, 3 and 6. From Fig. 6 it appears that the compressive strength increases directly with the carbon content up to 1 per cent carbon, the relation for these data being expressed by $S_c = 37{,}000 + 55{,}000\ C$. Results of certain tests by Marshall, given in Table 1, show that the elastic limit in tension and compression are practically identical for all sizes of bar and also that the ultimate compressive strength of bars with $\frac{l}{d} = 12$ is the elastic limit. They also show the marked decrease in elastic limit and ductility for the large sizes of bar, all being rolled from the same billet.

TABLE 1.—MILD STEEL IN TENSION AND COMPRESSION

Comparison of Tensile and Compressive Results with Results of Tests on **Short Columns of Round** and Square Bars from $\frac{3}{4}$ in. to $2\frac{1}{2}$ in. in Diameter, all Rolled from one Blow of Bessemer Steel. Elongations measured on a length equal to ten diameters, by means of an extensometer similar to Fig. 37, Chap. II. (From Marshall's Experiments, *Trans. Am. Soc. C. E.*, Vol. 17, Tables 1 and 2.)

Size of Specimen.	Elastic Limit in Pounds per Square Inch.		Ultimate Strength in Pounds per Square Inch.		Elongation.		Reduction of Area. Percentage.
	In Tension.	In Compr. for $\frac{l}{d} = 2$.	In Tension.	In Compr. for $\frac{l}{d} = 12$.	Length of Specimen.	Percentage of Elongation.	
$\frac{3}{4}$	45,181	45,000	68 711	44,970	8	26.4	45.3
1	43,880	45,355	68,240	43,540	10	25.6	39.3
$1\frac{1}{4}$	40,903	42,880	67,506	40,455	12	26.4	43.0
$1\frac{1}{2}$	39,795	42,015	66,598	40,150	15	25.4	39.3
$1\frac{3}{4}$	39,105	41,225	66,366	39,700	18	21.3	33.3
2	38,207	39,176	65,663	40,300	20	23.9	27.8
$2\frac{1}{4}$	37,655	36,542	65,460	38,030	22	13.7	17.2
$2\frac{1}{2}$	36,100	36,840	....	35,650	25	10.2	
Means	40,103	41,129	66,935	40,350	....	21.9	35.0

The *shearing strength* of steel also increases with the carbon content, as can be seen from the results in Table 2. The test-pieces used in obtaining these results were subjected to double shear, due care being taken to avoid bending as far as possible.

From these data it appears that the ratio of the shearing strength to the tensile strength is approximately 0.80 for medium- and low-carbon steels, but decreases as the carbon content increases, being in the vicinity of 0.60 for high-carbon steels.

Fig. 7 shows the influence of carbon on the torsional strength and torsional ductility of $\frac{5}{8}$-in. round steel specimens of variable carbon content. The ratio of the computed twisting strength to the tensile strength for these steels varied from 1.1 for the low-carbon steels

TABLE 2.—SHEARING RESISTANCE OF STEEL

Kind of Steel.*	Per Cent. Carbon.	Number of Tests Averaged.	Tension Test.		Shearing Strength, Pounds per Sq. In.	Ratio of Shearing to Tensile Strength.
			Elastic Limit, Pounds per Sq. In.	Ultimate Pounds per Sq. in.		
Landore Siemens	....	2	37,500	57,000	47,500	0.829
" "	....	2	40,000	63,500	51,000	0.800
" "	....	3	37,000	64,000	52,000	0.811
" "	....	6	40,600	69,000	56,000	0.807
Weardale Bessemer	....	6	44,000	71,000	51,000	0.715
Bessemer	....	4	51,500	78,000	64,000	0.823
"	....	4	62,000	82,000	59,000	0.721
Crucible	....	2	69,500	116,000	74,000	0.632
Bessemer	....	2	70,000	118,000	79,000	0.670
Swedish Crucible	0.12	Average of a Large Number		55,800	41,500	0.740
	0.48			94,400	64,500	0.680
	0.71			126,100	82,000	0.650
	0.77			137,300	85,400	0.620

* Tests on Swedish crucible steels were reported by E. G. Izod in *Proc. Inst. Mech. Engr.*, 1906–1, p. 9; others by A. B. W. Kennedy in *Proc. Inst. Mech. Engr.* 1885, p. 262.

to 0.9 for the high-carbon steels. Since the true shearing strength is three-quarters of the modulus of rupture in torsion according to Upton's theory, the ratio of the true shearing strength in torsion to the tensile strength varied from 0.82 for the low-carbon steels to 0.67 for the high-carbon varieties. These ratios are in good agreement with the values computed from the transverse shear results of Table 2. The ratio of the elastic limit in torsion to the elastic limit in tension was more nearly constant, being approximately two-thirds for all carbon contents.

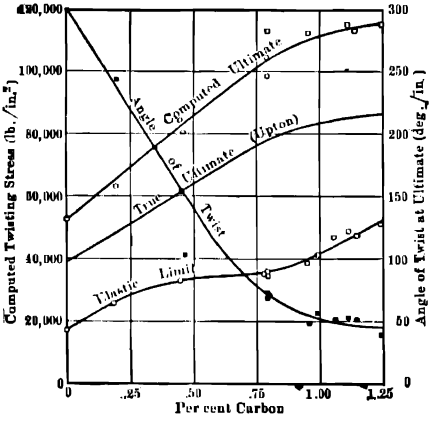

FIG. 7.—The Effect of Carbon on the Torsional Properties of Steel. Each point represents 3 tests on ⅝-in. round specimens. (*Tests of Metals*, 1881, p. 287.)

681. The modulus of elasticity of steel is nearly the same for tension and compression, and for either stress it is practically independent of the carbon content. This is shown in Figs. 2 and 3. Table 3 from Marshall's carefully conducted experiments * also furnishes comparisons of the moduli of elasticity for steels varying in carbon content.

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* Reported in *Trans. Am. Soc. Civ. Engr.*, Vol. 17, p. 62.

TABLE 3.—MODULI OF ELASTICITY OF STEEL ON FIRST LOADINGS, WITH VARYING PERCENTAGES OF CARBON, ONE SPECIMEN FROM EACH HEAT. (MARSHALL)

Number of Heats and Tests.	Average Percentage of of Carbon.	MODULI OF ELASTICITY E, IN POUNDS PER SQUARE INCH.			Kind of Steel.
		Lowest Value.	Highest Value.	Average Value.	
33	.09	28,750,000	31,540,000	29,924,000	Bessemer
8	.11	29,210,000	30,670,000	30,020,000	Open-hearth
107	.24	28,310,000	31,180,000	29,996,000	"
89	.34	28,140,000	30,910,000	29,672,000	Bessemer
25	.72	28,680,000	30,860,000	29,919,000	Open-hearth
			Weighted mean value =	29,866,000	

TABLE 4.—COMPARISON OF MODULI OF ELASTICITY IN TENSION AND COMPRESSION. (MARSHALL)

All results given in one-thousand-pound units, identical material.

STEEL.—Tensile Strength less than 100,000 Pounds per Square Inch.				
Size of Bar, In.	TENSION.		COMPRESSION.	
	E_1 First Loading.	E_2 Second Loading.	E_1 First Loading.	E_2 Second Loading
1 rd.	30,190	34,420	29,450	29,740
$\frac{5}{16}$ sq.	29,850	29,850	28,070	29,010
1 rd.	29,280	29,500	28,780	29,420
$\frac{3}{4}$ rd.	29,830	29,150	28,580	29,420
$\frac{5}{16}$ sq.	29,120	29,610	28,380	28,670
1 rd.	29,550	29,630	28,680	28,830
1 rd.	29,240	29,960	30,070	30,490
1 rd.	29,400	30,420	28,980	29,790
1 rd.	30,000	30,370	29,260	29,810
Mean	29,529	30,371	28,884	29,464

SPRING-STEEL.—Tensile Strength 144,000 Pounds per Square Inch.				
Size of Bar, In.	TENSION.		COMPRESSION.	
	E_1 First Loading.	E_2 Second Loading.	E_1 First Loading	E_2 Second Loading.
1 rd.	29,480	29,760	28,880	29,300
1 rd.	29,390	29,580	28,880	29,200
$\frac{5}{16}$ sq.	28,880	29,420	29,090	29,220
$\frac{3}{16}$ sq.	29,200	29,200	29,090	29,350
Mean	29,237	29,490	28,985	29,267

Table 4 shows that the modulus of elasticity of steel on second loading is likely to be slightly higher than on first loading due to very small set, although the primitive loading does not exceed the limit of proportionality. If the primitive loading exceeds the proportional limit, the modulus of elasticity is lowered, in some cases from 10 to 20 per cent. From a consideration of the available experimental data, it appears that the modulus of elasticity of steel in tension or compression generally lies between 28,500,000 and 31,000,000 a mean value being about 29,500,000 lb. per square inch.

A very large number of tests by Brinell on the modulus of elasticity of steels show also that heat treatment has little effect on the modulus of elasticity of carbon steels regardless of their carbon content. Annealed steels and quenched steels gave moduli averaging from 3 to 4 per cent higher than the bars received from the rolls.*

The modulus of elasticity in shear (often called the modulus of rigidity) is determined from torsion tests. Bauschinger reported tests † on Bessemer steels varying in carbon content from 0.19 to 0.96 per cent and on open-hearth steels of five degrees of hardness. For the Bessemer steels the shearing modulus varied from 11,900,000 to 12,700,000 lb. per square inch, and for the open-hearth varieties it ranged between 11,500,000 and 12,250,000 lb. per square inch. Platt and Hayward ‡ also reported values of the shearing modulus of elasticity for high- and low-carbon steels,—Bessemer, crucible and open-hearth varieties being represented. Their results ran from 12,350,000 to 14,000,000 lb. per square inch. For low- and medium-carbon steels an average value of the shearing modulus is 12,000,000 lb. per square inch.

682. Influence of Carbon on Ductility.—The ductility of steel decreases markedly as the carbon content increases (Figs. 4 and 5). Since ductility is also much influenced by variations in heat treatment and by the gauge length (Art. 711 and 106) it is not possible to give an accurate equation between ductility and carbon content. The following equations between per cent elongation (e) and per cent carbon (C), or strength (S_t), are examples of some of the attempts to express such relationships.

$e=\frac{3}{C^2+0.1}$, by Howe for elongation in 8 in. . . . . (1)

$e=32-30\,C$, by Upton for specimens having diameter of 0.8 in. and 8 in. gauge length. (2)

$e=50-48\,C$, by Upton for $\frac{1}{2}$-in. standard test-piece . . . . (3)

$e=\frac{1,800,000}{S_t-10,000}-10$, by J. B. Johnson for elongation in 8 in. . . . . (4)

$e=\frac{1,500,000}{S_t}$, by a Committee of Am. Soc. Civ. Engr . . . . (5)

The range of values for C in Eq. (1) to (3) is from 0 to 1 per cent. Eq. (1) gives values about 5 per cent too low for medium-carbon steels. Equations of the same type as 5 are common in specifications. For the high-carbon steels, however, this equation calls for too great elongation. Therefore, the constant is reduced in specifications for such steels.

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* *Jour. Ir. and St. Inst.*, Vol. 60, p. 234.

† See Unwin's *Materials of Construction*, p. 241.

‡ *Proc. Inst. Civ. Engr.*, Vol. 90, p. 409.

Fig. 8 shows the elongation field as worked out from a table in Howe's *Metallurgy of Steel*, which gives values of greatest and least elongations for different steels. It is plain from the figure that Eq. (4) has a much wider range of application than Eq. (5) or others of that type (5').

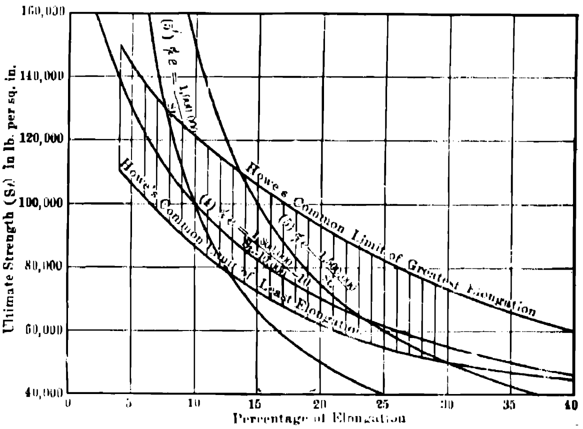


FIG. 8.—Relations of Elongation to Strength for Steels.

The per cent reduction in area (R) also decreases as the carbon content increases. In Fig. 4 the relation may be approximately expressed by

$$R=\frac{13}{C^2+0.18}.$$

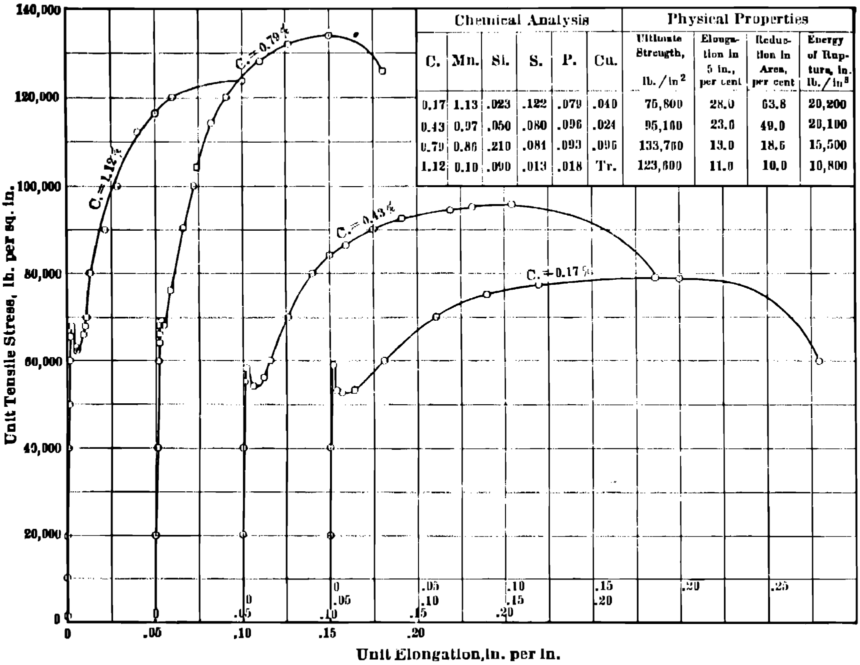
683. Changes in the Shape of the Stress diagram.—The effects of carbon on the tensile properties of steel are well shown by the changes in the shape of the stress-diagram. Thus, in Fig. 9 the increases in the elastic limit and ultimate strength and the accompanying decreases in the elongation cause the diagrams to increase in height and decrease in width. The horizontal portion of the curve for low-carbon steel, which follows the drop in the load after the yield point has been passed, disappears in the diagrams for the high-carbon specimens. The downward slope of the portion of the stress-deformation curve beyond the maximum stress becomes less pronounced in the high-carbon steels and disappears in the diagrams of the very hard steels which break without necking. Furthermore, the area of the diagram, representing the energy of rupture, decreases as the carbon increases (Fig. 9).

684. The resistance of steel to heavy shocks or blows decreases as the carbon content increases. The decrease in shock resistance is most rapid as the carbon is increased from 0.15 to 0.40 per cent. Fig. 33 shows some of Brinell's impact results which emphasize this conclusion. The figure also shows that the energy of rupture computed from tensile tests is a poor measure of resistance to impact. Similar evidence showing discrepancies between the energies of rupture in tension and impact is furnished by data of the Alloys Research Committee * as compiled by Howe in the discussion of a paper on impact testing before the Institute of Mining Engineers.†

* *Proc. Inst. of Mech. Engr.*, 1904–1, p. 160.

† *Trans. Am. Inst. of Min. Engr.*, Vol. 53, p. 218.

Although it appears that the soft and medium-carbon steels as rolled, or in the annealed state, have much superior resistance to impact than the high-carbon steels, we must not infer from this conclusion that the low-carbon steels are best suited to withstand repeated stress or a succession of light blows. Under such loadings, the harder steels with a higher elastic limit have proven more satisfactory. (See Art. 827.)



Chemical Analysis						Physical Properties			
C.	Mn.	Si.	S.	P.	Cu.	Ultimate Strength, lb./in²	Elongation in 5 in., per cent	Reduction in Area, per cent	Energy of Rupture, in. lb./in³
0.17	1.13	.023	.122	.079	.040	75,800	28.0	63.8	20,200
0.43	0.97	.050	.080	.096	.024	95,100	23.0	49.0	20,100
0.79	0.86	.210	.081	.093	.096	133,700	13.0	18.6	15,500
1.12	0.10	.090	.013	.018	Tr.	123,600	11.0	10.0	10,800

FIG. 9.—Tension Stress-diagrams of Carbon Steel Bars Used for Endurance Tests of Shafting. (*Tests of Metals*, 1889, p. 389; 1891, p. 603.)

685. The Range in Composition of Structural Steels.—Practically all steels used in engineering construction in the normal or annealed condition are of less than eutectoid proportion (0.83 per cent carbon). The carbon content is the result of experience whereby the proper combination of strength, elasticity, hardness and workability have been obtained to fit the material for the particular service. Increased tenacity and elasticity are gained at the sacrifice of ductility and softness. In structural steels, boiler plate, and the like, where some increase of strength is desirable, provided there is not too great loss of ductility and softness, a carbon content of about 0.20 per cent is customary. The tensile strength of the iron is thereby increased by about 15,000 lb. per square inch (from 45,000 to 60,000) without material loss of the ductility and softness so essential to the requirements for manufacture and service. In steel rails, there is little fabrication of the finished product and the stresses are heavy shocks at intermittent periods. Hardness is essential for wear, and high strength and elasticity are necessary to enable the steel to withstand the load and recover its alignment; yet ductility cannot be sacrificed to the extent of dangerous brittleness. The carbon content of rails varies from 0.50 to 0.90 per cent, the larger amounts having been introduced in special cases in recent years, particularly in heavy sections and where the steel has the minimum of phosphorus, sulphur, or other associated detrimental elements, which lower ductility without the compensating advantage of adding much strength.

The following table shows classifications,* approximate composition and mechanical properties of some of the more important steels used in construction. Carbon contents for tool steels may be found in Art. 709.

Classification Based on			Per Cent Carbon.	Tensile Strength (lb./in.^{2}).	Per Cent Elongation in	
Usage.	Hardness.	Manufacture.			8 in.	2 in.
Rivets and Welding......	Extra soft	O. H.	0.08-0.15	45- 55,000	30	
Tubing and Pressed Metal	Extra soft	O. H.	0.08-0.15	45- 55,000	30	
Screw stock.............	Mild or Soft	O. H. Bess.	0.10-0.20	55- 65,000	25	
Boiler plate............		O. H.	0.10-0.20	55- 65,000	25	
Structural..............		O. H. Bess.	0.15-0.25	60- 72,000		
Structural..............	Medium	O. H.	0.20-0.35	65- 75,000	22	
Machine.................	Medium	O. H.	0.20-0.30	60- 70,000	23	
Car axles...............	Medium hard	O. H.	0.40-0.55	75-100,000	..	12-15
Rails and Tires.........	Hard	O. H.	0.50-0.90	90-130,000	..	10-12
Springs.................	Extra hard	O. H.	0.85-1.05	125-150,000	..	8-10

EFFECTS OF PRINCIPAL IMPURITIES ON STEEL †

686. General Effects.—As we have seen in Chapter XVIII, it is not feasible under present practice to remove impurities entirely in making either iron or steel. Therefore, the final product always contains, besides iron and carbon, small percentages of the metallic impurities,—silicon, manganese, sulphur, and phosphorus,—together with lesser amounts of the oxides of silica, manganese and iron, silicates of manganese and iron, and some occluded gases. Occasionally very small percentages of copper and arsenic are also present. In well made steel the total amount of these impurities generally ranges between 0.2 and 1.0 per cent and their resultant effect on the constitution of steel is often very small. Of the common impurities, phosphorus and sulphur are injurious elements present in the ore which cannot be eliminated in the process of manufacture, whereas most of the silicon and manganese are introduced to improve the metal. The non-metallic impurities are objectionable substances which find their way into the steel during the process of refining.

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* See also S.A.E. classification system, Appendix B.

† For a discussion of the effects of impurities on steel, see paper and bibliography by J. E. Stead, *Jour. Ir. and St. Inst.*, Vol. 94, pp. 5–136.

687. Effects of Silicon.—Silicon probably in the form of iron-silicide, forms solid solutions with iron in all proportions up to 20 per cent. It is often added to molten metal to remove oxygen and diminish blowholes. In the carbon steels silicon rarely exceeds one-half of one per cent and in structural steels it is generally under a quarter of a per cent. With such small proportions of silicon the microscope reveals no peculiarities in constitution. Silicon up to 1.75 per cent appears to increase both ultimate strength and elastic limit without decreasing ductility.* Brinell's researches show that silicon increases the hardness of steel. For silicon varying between 0.10 and 0.60 per cent the increase in hardness was approximately 6.4 (Brinell scale) per 0.1 per cent increase in silicon. Silicon is, therefore, about one-third as effective as carbon in increasing hardness.

On account of the marked tendency of silicon to prevent solution of carbon in iron (Art. 662) it is very necessary to avoid prolonged heating at high temperatures in treating steels having high silicon and carbon contents. Instances have been recorded where steel castings have been ruined by soaking for a long time at a temperature considerably above the recalescence point, the combined carbon being thus transformed into graphite and the casting thereby greatly embrittled. However, with normal percentage of silicon and good heat treatment graphite is not present in steel.

688. Effects of Phosphorus.—When present in the low proportions common to steel, phosphorus exists in a solid solution of iron-phosphide (Fe_3P) and iron. In this form it permeates both the free ferrite and that composing the pearlite (Sauveur). By some it is considered to promote enlargement of the grains and thus produce brittleness. Howe maintains that the presence of phosphorus in ferrite makes the ferrite more mobile when it is slowly cooling through the transformation range. This mobility results in the banding of the ferrite into thin rods or layers which, upon etching, are revealed as light-colored lines, called ghost lines. Such formations, of course, render the metal less homogeneous.

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* The properties of silicon steels are discussed in Art. 734.

In wrought iron much of the phosphorus content is held in the slag fibers in the form of iron phosphate. As a constituent of the slag its effect is probably less detrimental than as a phosphide in the ferrite.

Although the ductility of low-carbon steel may be slightly decreased by the presence of 0.3 to 0.5 per cent phosphorus, the yield point, ultimate strength and hardness are increased. Resistance to shock is, however, markedly reduced by such high percentages of phosphorus. Tests by D'Amico on low-carbon steels show that toughness is adversely affected (i.e., the metal is rendered cold short) by 0.1 per cent phosphorus and very much decreased by 0.2 per cent of this element. The evil effect on toughness appears to be more pronounced in high-carbon than in low-carbon steels.

Although it is very probable that many failures have been erroneously ascribed to a high phosphorus content which, if all facts were known, were traceable to other causes, yet a due regard for the tendency to produce cold shortness requires that phosphorus be kept low in steel. At present the maximum limits are: for inferior grades of structural steel 0.1, for best grades of structural steel 0.05, and for tool steels 0.02 per cent.

689. Effects of Sulphur.—Sulphur readily combines with iron to form iron sulphide (FeS) which, when present in iron or steel, has a tendency to segregate and form brittle networks at the grain boundaries. On account of its low melting-point, iron sulphide causes a lack of cohesion between adjacent grains of the metal when it is heated above a red heat. Such brittleness at high temperatures is termed red shortness. Since red shortness makes steel or iron hard to roll or forge, it is a serious defect in the metal from the standpoint of the manufacturer. Manganese sulphide has a much higher-melting point than iron sulphide and does not render ferrous metals red short. Therefore, inasmuch as manganese has a very powerful affinity for sulphur, it is possible to relieve red shortness by adding sufficient manganese to the molten metal to combine with the sulphur. Theoretically the ratio of manganese to sulphur should be 1.7 to 1 in order to form manganese sulphide (MnS) and completely satisfy sulphur. Levy contends, however, that even if manganese is present in sufficient quantities to form the sulphide some iron sulphide will still remain and will be found mixed with the manganese sulphide. Since manganese sulphide also segregates and forms brittle masses, more or less rounded in castings and elongated in mechanically worked pieces, it appears that either sulphide causes a lack of homogeneity.

If sufficient manganese is present to prevent red shortness there is little evidence that sulphur in quantities less than 0.15 per cent exercises any appreciable effect on the mechanical properties of structural steel.* For screw-stock a high sulphur content (0.10 to 0.15 per cent) is commonly specified, since chips of such metal crumble without curling and the stock threads nicely. There appears to be a feeling, even though there is little direct evidence to support it, that percentages of sulphur too small to produce red shortness in rolling may develop invisible flaws in the finished metal. Specifications for steel, therefore, stringently limit sulphur to practically the same amounts as phosphorus.

690. Effects of Manganese.—Manganese is one of the main elements of the recarburizers used in manufacturing steel. Through its strong affinity for oxygen and sulphur manganese acts as a cleanser of the molten metal by withdrawing much of these undesirable impurities into the slag. When more manganese is present than required to satisfy sulphur and oxygen the excess manganese forms the carbide, Mn_3C, which is associated with cementite. If present in this form it acts as a hardener. In carbon steels, the manganese content is generally under 1 per cent and ordinarily runs about 0.3 to 0.6 per cent. Brinell's tests show that manganese, when under 1.0 per cent, hardens steel slightly, the average increase in hardness due to an increase of 0.1 manganese being about 4.0 on the Brinell scale. Howe † claims that a maximum fineness of grain together with a minimum of injury in hardening can be secured for carbon steels by maintaining manganese high, say around 1.25 per cent.

In high-carbon alloys manganese increases the solubility of carbon in iron and hinders the precipitation of graphite in cooling.

691. Copper up to 0.5 per cent appears to have little if any effect on the mechanical properties of steel. A small percentage of it is said to increase resistance to corrosion. In most steels the proportion of copper is negligible.

692. Arsenic is occasionally found in very small proportions in steels made in Europe. It has a tendency to raise the strength and cause brittleness. It is considered undesirable when more than 0.1 per cent is present.

693. Non-metallic Impurities.—Steel and iron also frequently contain very small percentages of the oxides and silicates of both iron and manganese. These impurities are mechanically suspended in the metal and are often called slag inclusions. They appear to arise from trapping of the slag, from the cleansing action of the recarburizer, and from the spalling of the ladle and furnace linings. In well-made steel such inclusions are slight and of small moment. If segregated they are likely to cause brittleness.

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* See data presented by J. S. Unger in *Engr. News*, Vol. 75, p. 363.

† *Proc. A. S. T. M.*, Vol. 17, Pt. 2, p. 8.

From time to time the opinion has been advanced that nitrogen and hydrogen are present in iron and steel, especially in Bessemer steel, and that they embrittle the metal. Some quantitative evidence of these facts is given in *Proc. A.S.T.M.*, Vol. 37, Pt. 1, p. 102.

EFFECTS OF HEAT TREATMENTS

694. Effects of Heating above the Critical Range.—On heating steel past the critical range of temperature, there is a structural change from an aggregate of ferrite and cementite to a homogeneous solid solution. This transition effectively destroys all pre-existing crystallization, not only as to type of aggregate, but of size as well.

Referring to the constitution diagram, Fig. 1, Ch. XXI, it will be noted that so long as a steel of carbon content 0 to 1.7 per cent is not heated above Ac_1 (723° C.) there will be no change in the structural relations of the iron and the cementite.* With rise of temperature above this critical point, however, formation of austenite will begin, and proceed to a degree dependent upon the carbon content of the steel and the temperature attained above the critical one. Solution of all of the pearlite is completed immediately the temperature exceeds Ac_1.

For hypoeutectoid (below 0.83 per cent C) or hypereutectoid (above 0.83 per cent C) steels the solution of the excess ferrite or cementite, respectively, proceeds with each degree of temperature rise above Ac_1, but is not completed until the temperature reaches the upper transition limit, marked by *GP* and *PS*, respectively, corresponding to the particular carbon content of the steel under treatment. In other words, the austenitic state in a steel of eutectoid composition (0.83 per cent C) is entirely brought about by heating to or just above the constant critical temperature of transition; while for a steel of other carbon content, a range of temperature is necessary, which is greater the farther the carbon content is removed from 0.83 per cent. The temperature necessary to accomplish complete solution of the cementite is higher the more the steel varies either way from eutectoid proportions. The transition, as noted heretofore, is the result of allotropy in the iron; cementite is immiscible in alpha iron, but is completely soluble in gamma iron, within the saturation limits, marked by region IV in the constitution diagram.

695. Effects of Cooling from above the Critical Range.—There will be progressive aggregation of the austenite into grains which increase in size with rise of temperature, up to the fusion stage. That grain size which is attained as a result of the maximum temperature reached during heating, will be retained during the cooling of the steel to ordinary temperatures, and, although the transition from the austenitic to the pearlitic (or some intermediate) form will take place during the critical temperature range, the final structure will exhibit such coarseness of texture as was inherent in the austenite when cooling began. Coarseness of grain is a function of temperature rise above the critical point Ar_3; but diminution of grain is not an accompaniment of temperature fall.

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* On account of lag in reaction the change takes place at Ac_1 which is slightly higher than Ar_1, the temperature of transformation on cooling.

Rate of cooling through and somewhat below the transition zone influences the final structure, however; (1) the reversion from austenite to ferrite-cementite requires time for its completion, and the quicker the cooling for a given composition, the less complete is the transition, and the more nearly the final product approaches austenite in structure and properties; this will be treated more fully in the discussion of tempering of steel; (2) the ferrite-cementite aggregate, particularly the pearlitic portion, will have opportunity for greater coalescence of like to like, the slower the cooling.

696. Relation of Grain Size to Mechanical Properties.—With like constitution, it appears to be generally true that ductility, toughness and resistance to fatigue, see Art. 821, increase with diminishing size of grain. The grains are aggregates of crystals, each of the same form and of like *orientation* which latter is not the same, except by coincidence, in the adjoining grains. The larger the separate aggregates making up the individual grains, the less there are for a given cross-section of material, and the more direct will be the path of fracture along the cleavage planes within the grain, or following the boundaries of contact of the separate grains. The weakness due to coarse grain is likely to be especially pronounced under vibratory or repeated stresses, since a fracture, once started, has a less broken course in attaining such dimensions that failure becomes inevitable even under loads which are apparently within the margin of safety. Coarse grain also lessens the resistance of steel to impact.

697. Annealing of steel consists in heating to a temperature near its critical range (723–910° C.) and then cooling, usually at a slow rate. It is done to attain one or more of the following objectives: (1) refine the grain, (2) soften the metal, (3) remove internal stresses, (4) change ductility, toughness, electrical and magnetic properties, (5) remove gases.

Full annealing is accomplished when the steel is uniformly heated 20 to 50° C. above the critical range and then slowly cooled through the range. In *process annealing* the part is heated to a temperature just below the critical range (550–650° C.) and cooled as desired. *Normalizing* is performed by uniformly heating to a temperature 30 to 60° C. above the critical range and cooling in still air at ordinary temperature. *Patenting* consists in heating alloys having an iron base above the critical range and then cooling below that range in air or molten lead which is held at a temperature about 365° C. *Spherodizing* is a prolonged heating of the metal at a temperature just below the critical range, followed by slow cooling. This nodulizes the cementite.

Steel slowly cooled through the solidification range is bound to be coarsely crystalline, and slow cooling through the austenitic and pearlitic ranges causes coalescence of like structural components. These conditions produce weakness and brittleness, which are especially marked in large steel castings. Pronounced improvement in structure and properties can be obtained by judicious annealing.

The rate of heating should be slow enough to permit uniform diffusion of heat throughout the piece. The specific treatment will vary with the amount of carbon and other constituents in the steel, with the size of the object, and with the relations of hardness, strength, and ductility, which are desired in the final product. Soft steels require a higher temperature than those more nearly approaching eutectoid proportions, since the complete conversion to austenite is affected only by heating past the upper critical temperature. Simple annealing of mild steels does not produce as great a refining of grains as is obtained with eutectoid steels, since the aggregation of the eutectic begins at the common lower critical temperature, while the higher end-temperatures for the lower-carbon steels allow greater coarseness of the newly formed grain. The range of annealing temperatures suitable to various carbon steels is well shown in Fig. 10.

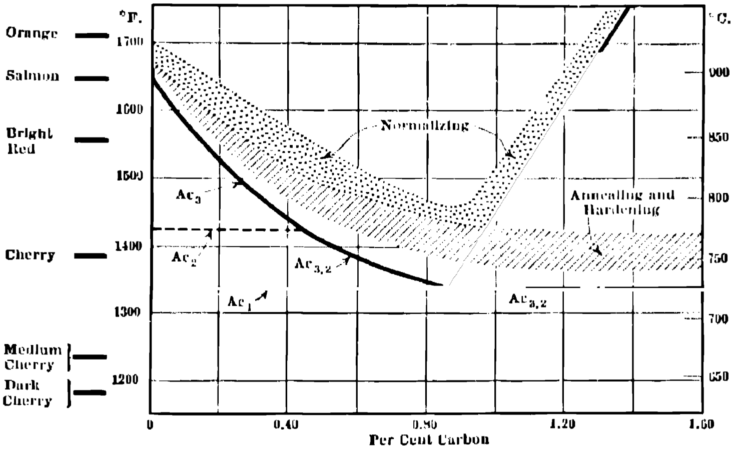

FIG. 10.—Temperatures for Normalizing, Annealing and Hardening Carbon Steels. (From *Metals Handbook*, 1939, p. 993.

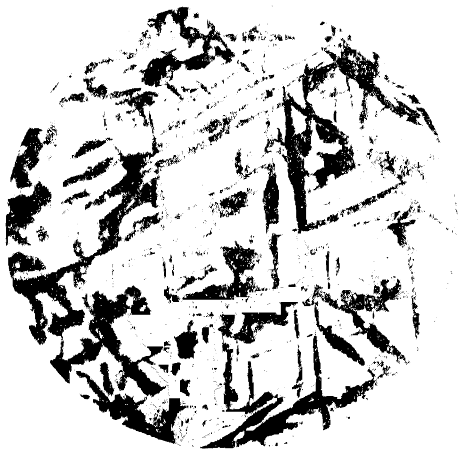

FIG. 11.—Coarse Structure in a Steel Casting Due to Slow Cooling.

This diagram shows that the temperature range within which annealing may be done well is wider for high-carbon than for low-carbon steels. For hyper-eutectoid steels the range is constant, between 740 and 770° C. The temperature range for successful normalizing is a narrow belt above the upper *Ac* line.

Heating should be by gradual approach to the desired temperature, and the object should be held at this temperature for a sufficient time to reach a uniform condition throughout. This time varies with the size of object; about an hour for each inch of thickness should suffice.

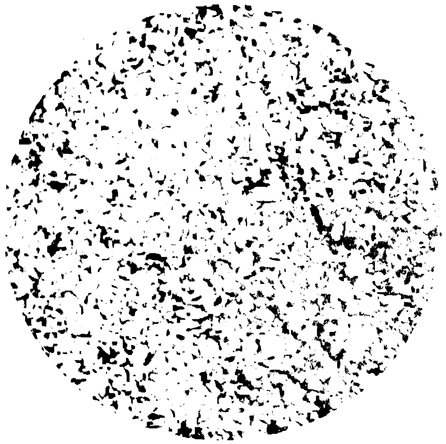

FIG. 12.—Same Steel Casting after Forging Showing a Much Finer Grain than Fig. 11.

Temperature of annealing fixes the grain size of the product. It should always be the lowest possible to effect complete refining. Rate of cooling from this temperature also has a pronounced effect on the physical properties. Rapid cooling results in incomplete reversion of the austenite to pearlite to a degree which varies with the carbon content of the steel and the rapidity of cooling. This is a process of hardening, and is treated in greater detail later. Provided cooling is slow enough to enable the steel to revert to the pearlitic condition, the aggregation of its cementite ferrite constituents will be coarser the slower the cooling, and the greater softness and ductility are thus obtained at a sacrifice of some strength and elasticity. Cooling in the furnace or imbedded in lime, clay, etc., is slow; quiet air or an air blast is more rapid, and is usual for large objects unless abnormal softness is desired, or the carbon content of the steel is high.

Small pieces should always be protected from oxidation and consequently decarburization of the surface during annealing. This may be partially accomplished by surrounding the parts with lime, sand, or pulverized charcoal. It may be very effectively done by the Jones method. This consists in placing the material in a closed tube from which the air is expelled by a non-oxidizing gas which is kept constantly flowing through the tube. Surfaces of parts thus treated are bright and untarnished. Metcalf also uses a tube closed with a loosely-fitting cap. The air is almost entirely expelled from the tube by the volatilization of resin which is placed in the end of the tube farthest from the cap. Parts annealed by the Metcalf method are slightly tarnished but decarburization is negligible.

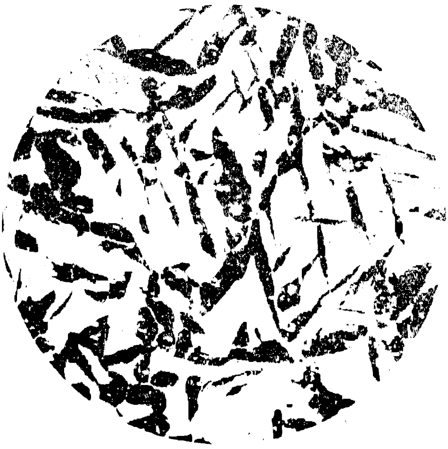

Fig. 13.—Same Steel Casting Annealed at too High Temperature (1100° C.). Note the Coarse Grain.

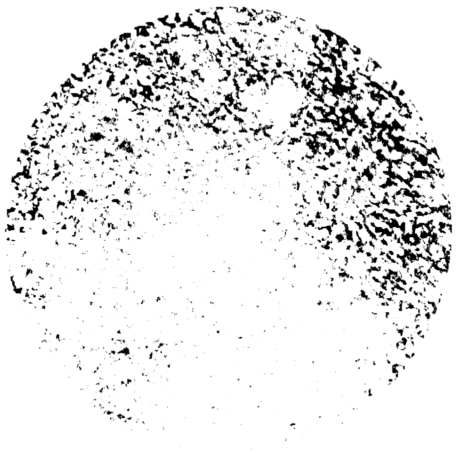

Fig. 14.—Steel Casting of Fig. 13 after Annealing at 800° C.

The changes in size of grain brought about by certain heat treatments of a piece of 0.50 carbon steel are shown in Figs. 11 to 16. The coarse structure of the steel as cast (Fig. 11) was materially reduced by forging (Fig. 12), but reheating of the forged steel to 1100° C. again produced a coarse grain (Fig. 13). A fine grain (Fig. 14) was given this overheated steel by annealing at 800° C., which is approximately the proper temperature for annealing this grade of steel. (See Fig. 10.) A still finer grain showing a very tough steel was produced by a double quenching treatment. The steel was first quenched in water from a temperature of 1000° C. which made it very hard and gave it a fine structure appearing like interlacing needles and called martensite (Fig. 15). Subsequently it was heated to 650° C. and again quenched in water, with the result shown in Fig. 16. This represents the fine porcelainic structure of sorbite in which the transition from martensite to pearlite plus ferrite has been practically completed but without opportunity for coalescence of pearlite masses and ferrite grains as in annealing at higher temperatures. Sorbite is the structure which is characteristic of the toughest steels.

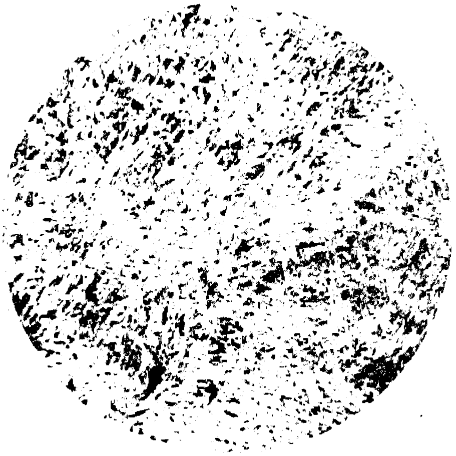

FIG. 15.—Same Steel Casting Heated to 1000° C. and Quenched in Cold Water Shows a Martensitic Structure. Structure indicates high strength, hardness, and brittleness.

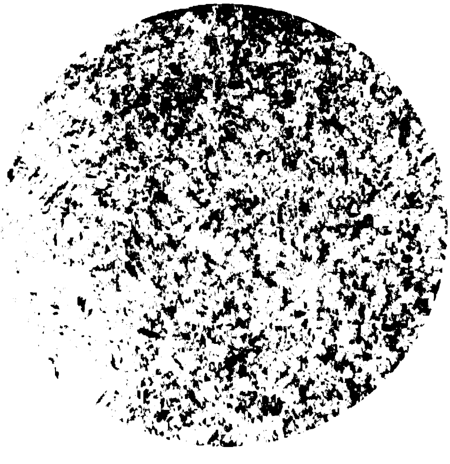

FIG. 16.—After Reheating the Casting of Fig. 15 to 650° C. and Quenching, a Sorbitic Structure Results. This structure connotes high strength and toughness.

698. Effects of Annealing on Mechanical Properties.—Referring again to Figs. 4 and 5, it is permissible to conclude that annealing from the temperature ranges shown in Fig. 10 reduces the strength, hardness, and elastic ratio but increases the ductility. The effects are most pronounced in steels having more than 0.5 per cent carbon and are of small moment in the very low-carbon steels.

The effect of temperature of annealing on the mechanical property of several tool steels is well illustrated by the experiments of S. v. Fabry, from which Fig. 17 has been prepared. Here again it will be noted that the properties of the high-carbon steels are much more affected by annealing than those of the medium-carbon steel. For all cases, it will be noted that the ductility is a maximum for temperatures at which the strength is a minimum and that the elevation in the per cent reduction in area is also most prominent at the same temperatures. These temperatures range from 700° for the 0.58 per cent carbon steel to 800° C. for the steel of 1.36 per cent carbon. It should also be observed that the minimum strengths of these steels are nearly the same but the corresponding percentages of reduction in area diminish as the carbon content increases. In general, the

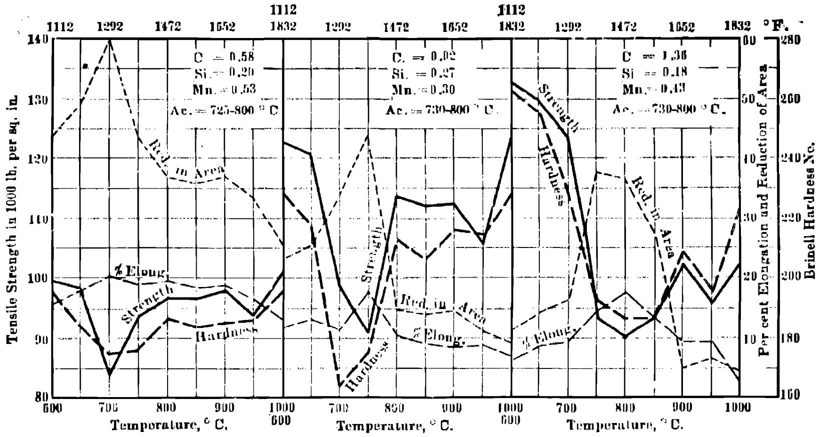

Fig. 17.—The Influence of Annealing Temperature on the Mechanical Properties of Tool Steels. (Fabry in *Proc. I. A. T. M.*, 1912.) Specimens 1.18 in. square were held at temperatures indicated for three hours.

curves of hardness and strength are nearly parallel. The microscopic data accompanying the original report indicate that the most uniform and the finest grained structures were produced by annealing at the temperatures corresponding to maximum ductility or minimum strength.

The effects of variations in annealing temperature on the strength and ductility of steels differing in carbon content are also shown in Fig. 29 and 30. From these data by Brinell it appears that the strength of the low and medium-carbon steels was little affected by any of the annealing temperatures. The strengths of the high-carbon steels were slightly increased by annealing at 350° C., slightly diminished by annealing at 750° C., and considerably increased by annealing at 1000° C. The ductility of all grades of steel was raised somewhat by annealing at 350° C. Further increase in ductility was secured by annealing at 750° C. Annealing at 850° C. produced the most marked increase in the ductility of the high-carbon steels. Annealing at higher temperatures effected a corresponding slight increase in the ductility of low-carbon steels, but the curves plainly show that these temperatures were too high to secure maximum ductility from the high-carbon steels.

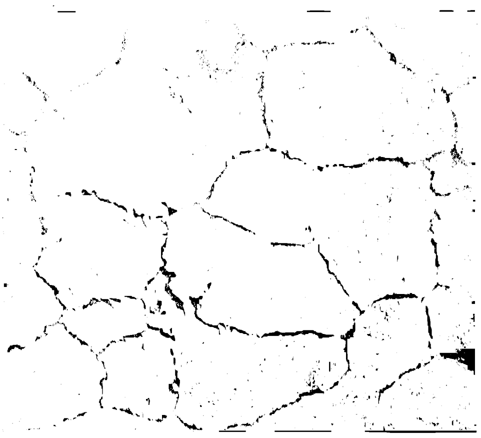

FIG. 18.—Showing Coarse Grain Produced in Rail of Fig. 19 by Overheating.

699. Overheating and Burning.—Exposing steel to temperatures considerably above the critical range develops a coarse grain; but if the temperature is not in region II of the constitution diagram (Fig. 1, Ch. XXI) for the particular carbon content, it is possible to effect complete refining by reheating above the critical range. The structure of Fig. 18 could be restored to that of Fig. 19 by proper annealing. If, however, the temperature of heating is such as to take the steel into region II, partial fusion results, and the steel becomes "burnt." There is mechanical separation of the grains due to the partial fusion and gas evolution, with probable accompaniment of some oxidation of the boundaries. Thus the steel becomes brittle or "rotten." Such an effect is not curable by reheating, or even by reheating and forging. The differences between burnt, overheated, and normal grains of a steel casting are well shown in Fig. 20.*

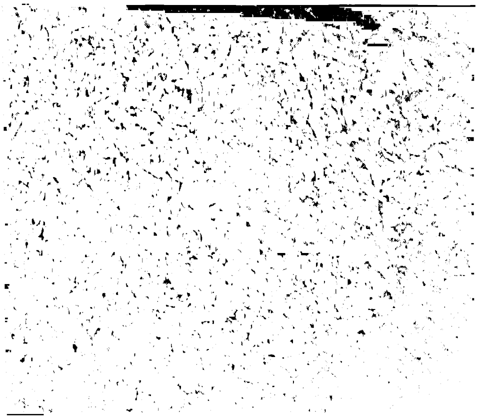

FIG. 19.—Structure of Rail after Rolling.

Although microscopic examination of sections of the metal subjected to overheating or burning will reveal the defective structure, it is not always convenient to make such an examination. The Metcalf test is simpler and effective in detecting overheating or burning in steels containing over 0.30 per cent carbon. For this test it is preferable to use a bar of steel about a foot long having the same carbon content as the maltreated piece, although the piece in question may be used. On opposite faces of the bar saw slots are cut to a depth of approximately one-eighth of the thickness of the piece at intervals of about one inch. One end of the piece is then stuck in a fire and heated until it scintillates. Upon removal it may be quenched or allowed to cool in air, depending upon treatment accorded the piece in question. The test-piece is then broken and, beginning at the burnt end, the fractures at the notches show a gradual change from very coarse grain to a fine silky structure for the section which was at the proper restoration temperature (i.e., just above the critical range); sections nearer the cooler end will show the original structure of the bar. A comparison of the fracture of the piece in question with the series of fractures indicates the treatment accorded.

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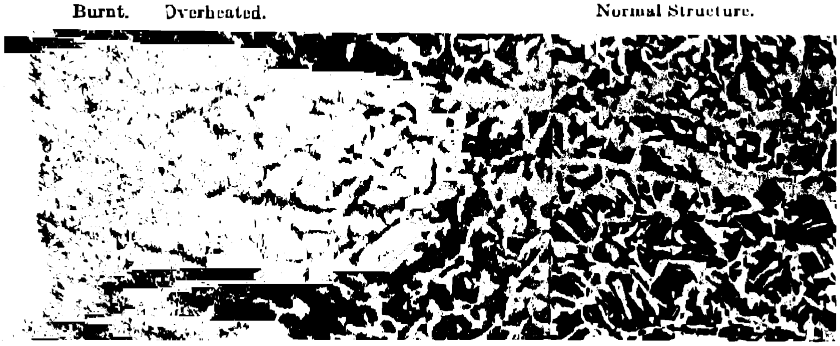
* For effects of overheating on rivet steel, see *Engr. News-Record*, Vol. 82, p. 280.

700. Theories of Hardening.—It has been known for centuries that some kinds of iron become very hard after heating to a bright red heat and quenching in water. In fact, this property was the basis of the older classification of certain products as "steel." Also, it has been recognized for a long time that this property is a function of the carbon content of the steel, and that no appreciable hardening accompanied the quenching of iron with negligible or very small amounts of carbon. But it is only since the development of our understanding of the iron-carbon relations that the hardening of steel by quenching has been put upon our present-day fairly rational basis, and that the heat treatment of steel has deviated from the method of "rule of thumb."



Actual width = 0.08 in.

FIG. 20.—A Steel Casting of 0.40 Per Cent Carbon Cut by an Oxyhydric Torch. Note gradation in structure from burnt metal at cut (on the left) to normal structure at right end.

Heat-treatment methods have reached a high degree of perfection; and the phenomenon as a whole is fairly well understood. Several theories of hardening are to-day in existence, each having its adherents and points of merit; yet none offer satisfactory explanation of all of the observed facts. Sauveur * classifies them as follows:

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* *Metallography and Heat Treatment of Iron and Steel,* p. 308.

- **Retention Theories**
  - Solution Theories
    - Beta Iron or Allotropic Theory.
    - Alpha Iron Theory.
  - Amorphous Iron Theory.
  - Carbon Theories
    - Hardening Carbon Theory.
    - Sub-carbide Theory.
- **Stress Theories**
  - Early Stress Theory.
  - Interstrain Theory.
  - Twinning and Amorphous Iron Theory.

The retention theories are based upon the restraining of certain reactions which take place normally when steel cools through the critical temperature ranges; very quick cooling through the transformation ranges suppresses the change, and the condition stable only at higher temperatures is retained to a greater or less degree in the cold rigid steel. According to the several theories, this may be (*a*) a hard, beta allotropic form of iron normal only to a limited temperature range between 780° and 880° C., which is assisted by solution of iron carbide Fe_3C, and its influence in restraining the normal transition; (*b*) a metastable solution of Fe_3C in alpha iron, suppressing, therefore, the separation of the carbide, but not the change from gamma to alpha iron; (*c*) a hard amorphous transition form, which is intermediate to the complete allotropic change in the iron, and which is aided in its effect by the solution of the combined carbon and its influence in slowing down the reaction velocity; (*d*) an allotropic form of iron carbide, inherently hard, or conferring hardness because of its forced solution in the iron; (*e*) a hard subcarbide of iron $Fe_{24}C$, stable only above the critical range.

According to the stress theories, steel cooled quickly from above the critical range is subjected to stresses due to the shrinkage of its outer shell on the interior, and to the increased volume accompanying the transformation of gamma into beta and alpha iron. Hardening accompanies the resultant straining of the metal. Theories in this class were among the first to be put forward to explain the hardening of steel and have recently attracted renewed attention. Hypotheses are advanced that (*a*) the transition of combined carbon from solution in gamma iron to non-solution in alpha iron is not completed, non-homogeneity of crystalline orientation is caused, and a hardness similar to that caused by interstrain is the result; (*b*) that severe internal strains due to quenching steel, cause crystal twinning and hard amorphous layers.

Many of the theories have much in common, and in some cases the distinctions are in large part technical or a matter of definition. The technical points are exceedingly complex and involve the highest principles of metallography in experimentation and elucidation. To quote Sauveur (Metal. and Hard. of Steel—*Int. Eng. Cong.*, 1915). " It will be obvious from the foregoing that the many attempts at arriving at a satisfactory explanation of the hardening of steel are based on one or more of the following conceptions; (1) existence of a hard allotropic variety of iron, (2) existence of solid solutions involving the occurrence of so-called 'hardening' carbon, and (3) existence of *strains* in quenched steel causing or not an amorphous condition of the iron."

"It will likewise be obvious that nothing so far presented fully satisfies our craving for a scientifically acceptable explanation of the many phenomena involved."

"It would seem as if the methods used to date for the elucidation of this complex problem have yielded all they are capable of yielding and that further straining of these methods will only serve to confuse the issue, a point having been reached when this juggling, no matter how skillfully done, with allotropy, solid solution, and strains, is causing weariness without advancing the solution of the problem. The tendency of late has been to abandon the safer road of experimental facts and to enter the maze of excessive speculations, in which there is great danger of becoming hopelessly lost. The conclusion seems warranted that new avenues of approach must be found if we are to obtain a correct answer of this apparent enigma."

Many of the theories are founded upon special or unusual conditions; others, again, fit the general observations but fall short of covering all of the facts. It seems logical to assume that since hardening in metals (including steel) can be the result of several physical effects, observed phenomena are not to be explained by theories based upon one principle only; there may be several contributing causes.

701. Essentials in Hardening.—The operation of hardening of steel consists of two essential steps: (1) Heating above the critical range of temperature; (2) cooling rapidly from that temperature. No change in the iron-carbon relations will take place until the steel is heated to the lower critical temperature Ac_1 (about 723° C.). Austenite will then begin to form, and the reactions will be completed at the upper transition temperature GPS of the constitution diagram, Fig. 1, Ch. XXI. As indicated by the diagram, and discussed more fully in Art. 661, complete conversion of a eutectoid steel (0.83 per cent C.) may be effected by heating to just above the constant temperature Ac_1; while for steels of other carbon content, a range of temperature is necessary, which becomes greater as the carbon content is farther removed either way from eutectoid proportions (Fig. 10).

The above transitions are reversible, under normal conditions, and the reactions will reach a condition of equilibrium with rise or fall of temperature, in accord with the constitution diagram. The essential reaction is ferrite plus cementite to austenite, or the reverse; or combined carbon into or out of solution with gamma iron. The reaction requires time; separation is relatively much slower than solution, and naturally requires longer time in proportion to the quantity of cementite to separate; that is, with increase of carbon content in the steel. Again, the reaction velocity of separation becomes less as the steel becomes colder and more rigid. Therefore, by suddenly cooling a steel which is in the austenitic temperature range, it is possible to bring it to such a temperature and state of rigidity that the reaction velocity becomes nil, and the austenite will be forcibly restrained in the steel at normal temperatures, in its entirety or in such intermediate transition form as might result from the carbon content and cooling conditions.

702. Methods of Hardening.—The quenching capacity of a medium for hardening steel depends upon its specific heat, conductivity, volatility, viscosity, and temperature. The hardening bath should always be kept at a uniform temperature, especially if water is used, and should be continually circulated to prevent the formation of vapor envelopes about the metal, since these materially retard the withdrawal of heat. In order of hardening capacity the more common quenching media rank thus: water spray, brine, water, oil and molten lead. The first two of these are used commercially on small parts only, when an extremely hard surface is desired. Files are often hardened in brine. Water quenching likewise is so drastic that its use is restricted to the low-carbon steels or to very small parts of simple shape made of high-carbon steel. With the heavy sections of high-carbon steel these drastic hardening agencies are likely to cause cracking.

On account of the wide range in quenching power which various oils possess and because their action on the steel is less severe than water quenching, they are much used for hardening tools, machine and structural parts where toughness is an important consideration. In some works the drastic cooling of the water-bath is somewhat relieved by floating an oil bath above it; in others the parts are partially cooled in water before being quenched in oil. The principal use of molten lead is for toughening the metal.

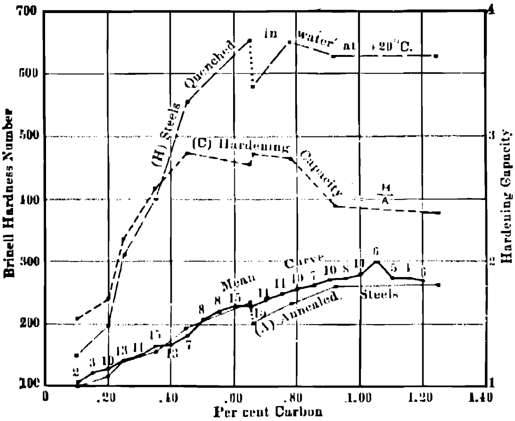

Fig. 21.—The Relations between Carbon Content, Hardness and Hardening Capacity, $\frac{H}{A}$. (Brinell in *Jour. Ir. and St. Inst.*, Vol. 59, p. 243.)

Figures beside plotted points indicate number of results averaged. The silicon content varied from 0.1 to 0.5 and manganese from 0.2 to 9.6 per cent in the steels represented by the mean curve. The discontinuity in curves *H*, *C*, and *A* at 0.66 per cent carbon is due to the lower manganese contents in the higher carbon steels.

Parts of irregular form are likely to warp and crack when rapidly hardened. Long pieces should be immersed in the bath end first wherever possible. If very long, such pieces may be allowed to roll into the bath. Inasmuch as it is almost impossible to harden uniformly pieces of large section they should, wherever possible, be bored before hardening. This is often advantageously done in heavy shafts and axles. The inferior metal at the center of the piece is thus removed; and, by forcing a stream of oil through the hole during quenching, a much more uniform hardening treatment is gotten.

703. Effect of Carbon on Hardening.—The influence of carbon in hardening steel is well brought out by the experiments of Brinell, some of the results of which are presented in Fig. 21.* It will be observed that the hardening capacity is greatest and nearly constant for steels containing 0.40 to 0.80 per cent carbon, but the maximum hardness is found in hardened steels of approximately eutectoid composition.

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* See also Figs. 4 and 5.

704. Characteristic Microscopic Structures in Hardened Steels.—Present definitions and nomenclature are taken largely from the Report of Committee 53 of the I.A.T.M. This report was based on the theory that the transformation of austenite to pearlite takes place in a series of steps. According to this theory, when austenite, of eutectoid composition, is cooled slowly below the critical range it transforms first to martensite, which being unstable transforms immediately to unstable troostite, which transforms to sorbite, and that in turn finally to lamellar pearlite. If a fast cooling rate is used, martensite or some other intermediate product will be retained. Further, according to the theory, reheating martensite slightly below 400° C. will produce troostite, and reheating to increasingly higher temperatures will produce in turn sorbite, granular pearlite, and finally lamellar pearlite.

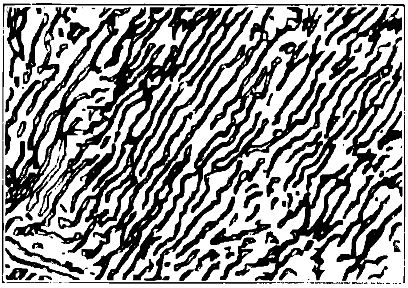

FIG. 22 (*a*).—Lamellar Structure in 0.73% C. Steel. Heated ½ hr. at 815° C. and cooled in furnace. (1500×. Both Figures by R. A. Ragatz.)

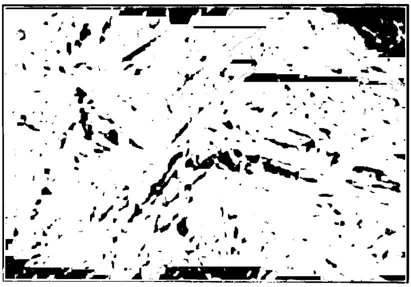

FIG. 22 (*b*).—Granular Structure with Evidences of Acicular Origin. Same steel quenched in caustic soda from 815° C. and reheated to 315° C. (1500×.)

This theory implies, and it was so considered for some time, that troostite and sorbite obtained by slow cooling directly from austenite are exactly similar to the troostite and sorbite obtained by reheating martensite to the required temperature. That this is not true is now universally recognized and is easily proved with the modern microscope. Majority opinion now agrees that if cooling is sufficiently slow the austenite of ordinary carbon steels transforms at temperatures, above 550° C. directly to lamellar pearlite, which structure is stable on further cooling. Also, if cooling is sufficiently rapid, the austenite will transform at temperatures below 150° C. to martensite. With the usual cooling methods this means that direct transformation from austenite will result in either lamellar pearlite or acicular martensite. If martensite is reheated, a granular structure is produced which contains increasingly coarser carbide particles as the reheating temperature is increased. Examples of the two structures are shown in Fig. 22*a* and Fig. 22*b*.

The following definitions of the names of the constituents of steel that have been commonly used and will probably continue to be used until changes are made by an international committee are those suggested by Committee 53, modified to agree with recent developments.

Austenite is a solid solution of carbon in gamma iron. It may also include other elements, manganese, nickel, etc., in association in the solution. The carbon may vary from traces to 1.7 per cent. Austenite is a normal constituent of all carbon steels above the critical temperature range, and may be retained in varying proportions by rapid cooling by quenching from these high temperatures. These proportions depend upon the amount of carbon, temperature of quenching, and speed of cooling. In plain low-carbon steels, there is no retention of austenite, due to the rapidity of transformation; with high carbon (above 1 per cent) a proportion up to about 50 per cent may be checked in association with martensite.

Associated metals, as manganese, nickel, tungsten, etc., in sufficient amount lower the critical temperature or slow down the rate of transition, so that it will not take place at all or will be checked by moderate cooling, with retention of austenite alone. Being a homogeneous solid solution it exhibits the characteristic polygonal grain structure. Fig. 23, is a typical microsection.

The physical properties of austenite vary with the carbon content; an increase of this element increases the hardness, strength and elasticity and lowers the ductility. Austenite is hard relatively to ferrite, but is softer than cementite, or than martensite of the same carbon content. Austenitic steels are non-magnetic, tenacious, rather ductile, and tough.

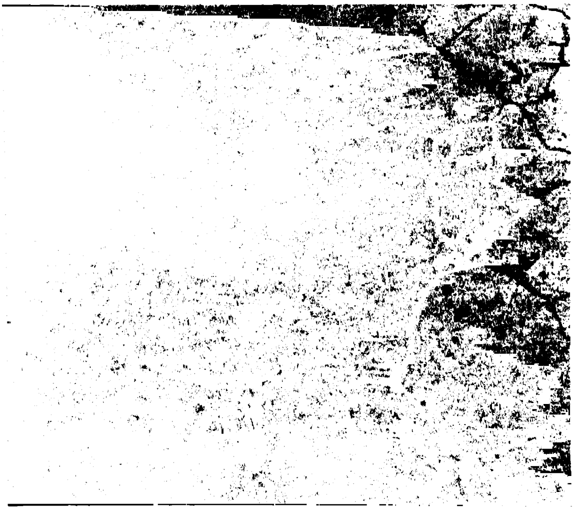

FIG. 23.—Cast Manganese Steel Quenched in Water from 1000° C. Nearly 100 per cent austenite. Mag. = 100 d. (From Fig. 325, Sauveur's *Metal. and Heat Treatment of Iron and Steel.*)

Martensite is the decomposition product that results when austenite is made to transform below 150° C. It is regarded as being an excessively supersaturated solution of carbon in alpha iron which undergoes a precipitation of carbide particles on reheating. It is the principal constituent of hardened carbon steels, and the cause of their great hardness. The exact cause for the hardness of martensite is still a moot point, but some of the more important reasons given are: precipitation of the carbides from the supersaturated solution, acicular structure, fineness of grain, distortion of the space lattice, and presence of internal strains.

Martensite is obtained, associated with austenite, by quenching very high-carbon steels from high temperature in ice water, or in total by water-quenching eutectoid or hypereutectoid steel from the austenitic temperature range. Microscopically, as shown in Fig. 24, the structure appears as a network of interlacing needles of triangular distribution, assumed to be cleavages of octahedra. Martensite is very hard, very strong, brittle, and non-malleable when cold. These properties are intensified with increasing additions of carbon.

Troostite has been regarded as the product obtained by quenching carbon steels from the austenitic region at a rate slightly slower than one that would produce a completely martensitic structure, or by tempering martensite between 200 and 400° C. The first type, called primary troostite, has a nodular appearance under low magnification, but higher magnification shows it to be very finely laminated pearlite. The second type, called secondary troostite, has a granular structure with finely divided carbide particles. Both forms are darkly colored by etching.

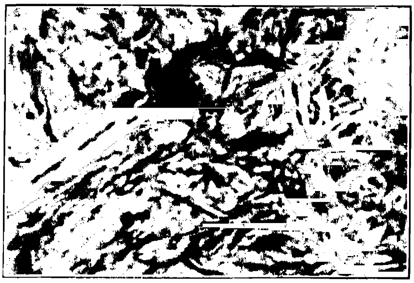

Fig. 24.—Acicular Structure of Martensite. A 0.73% C. steel quenched from 815° C. in caustic soda (1500 ×). (By R. A. Ragatz.)

Sorbite has been considered as forming in lighter sections of steel on cooling in air from above the critical range, by oil quenching steel of medium carbon content, or by reheating martensite above 400° C. but below the critical temperature. The first two methods produce lamellar structures, while the last method produces a granular structure with fairly coarse carbide particles (see Fig. 25).

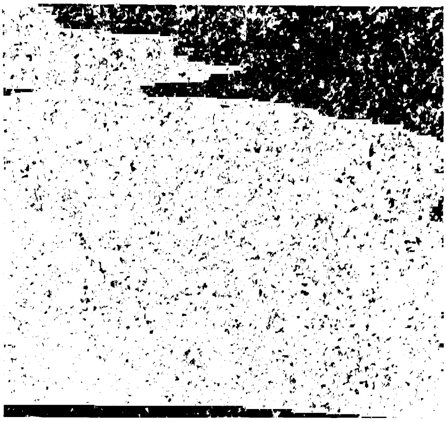

Fig. 25.—A 1.1 Per Cent Carbon Steel Quenched from 900° C. Reheated to 600° C. and Quenched, Showing Nearly 100 Per Cent Sorbite. Mag. = 150 d. (Courtesy Sauveur and Boylston.)

Because of their fine and homogeneous state of aggregation, steels made sorbitic by tempering martensite have high strength and elasticity coupled with maximum ductility compared with those of normal pearlitic structure.

Naturally, with no sharp boundaries between the constituents, tempered steel may be relatively complex, and consist of various associations of the transition forms. The extreme hardness and brittleness of martensite steels make them practically unsuited for industrial uses, except cutting tools; even here, and to a much greater extent in structural products, varying proportions of the other transition forms are desired. They are obtained by proper selection of composition of steel, maximum temperature of heating, nature of cooling medium, and by tempering; that is, reheating of the product to a prescribed temperature, followed by slow cooling or quenching.

705. Tempering.—A plain carbon steel that has been hardened is in a metastable condition of equilibrium. If this hardened steel is reheated to some temperature below the critical range, a more stable condition will be obtained. A low reheating temperature will begin the precipitation of the carbides from the unstable supersaturated alpha iron of the martensite, and with increasing temperatures the precipitation continues, followed by diffusion and coalescence. A long reheating period just below the critical will produce a spheroidized structure.

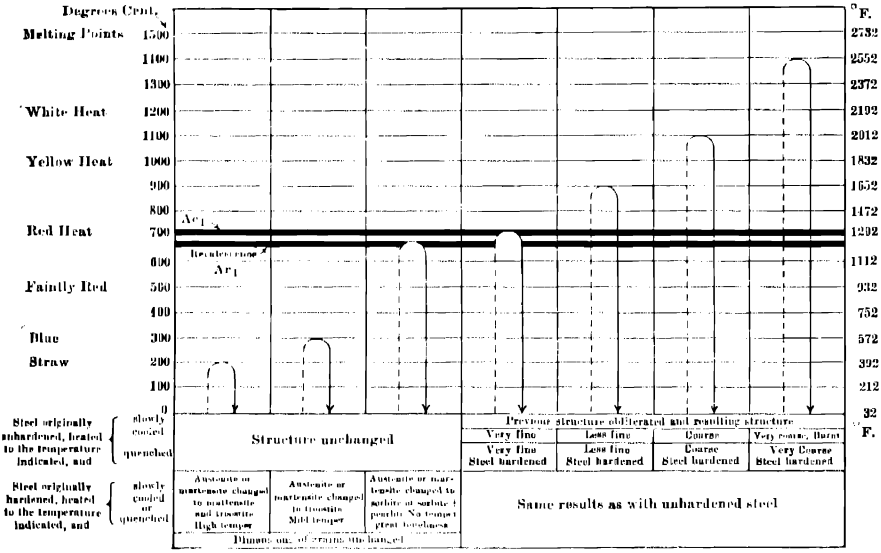

FIG. 26.—A Modification of Brinell's Hardening Chart, Showing the Changes Produced in High-carbon Steels by Heat Treatment.

A properly hardened steel will have maximum strength and hardness, minimum ductility and grain size, and will be internally strained. As the above combination of properties is usually not desired, modification is affected by tempering. *Tempering or drawing* consists in reheating a hardened steel to a temperature below the critical range and cooling as desired. The terms have been used synonymously by many, but some prefer to restrict the use of tempering to reheating temperatures below 400° C., and to use drawing where the reheating temperatures are above 400° C.

The reheating temperature to be used depends on the final properties desired in the steel. As this temperature is increased the strength, hardness, and internal strain decrease, while the ductility is increased. If good strength and hardness are desired, the steel is reheated to less than 400° C. The structure so produced is granular with fine carbide particles, and has been called troostite. It is entirely different from the structure produced by quenching austenite at an intermediate rate. If a greater measure of ductility, toughness, and freedom from internal strain is required, a higher reheating temperature, 400° to 600° C., is used. The structure so produced, called sorbite, is also granular, but impregnated with coarser carbide particles.

The rationale of hardening and tempering, and its correlation with the grain structure, is illustrated in Fig. 26.

706. Relation of Drawing Temperature to Hardness.—The effect of varying temperatures of reheating upon the hardness of water-quenched spring steels of different carbon contents is noted in Fig. 27.

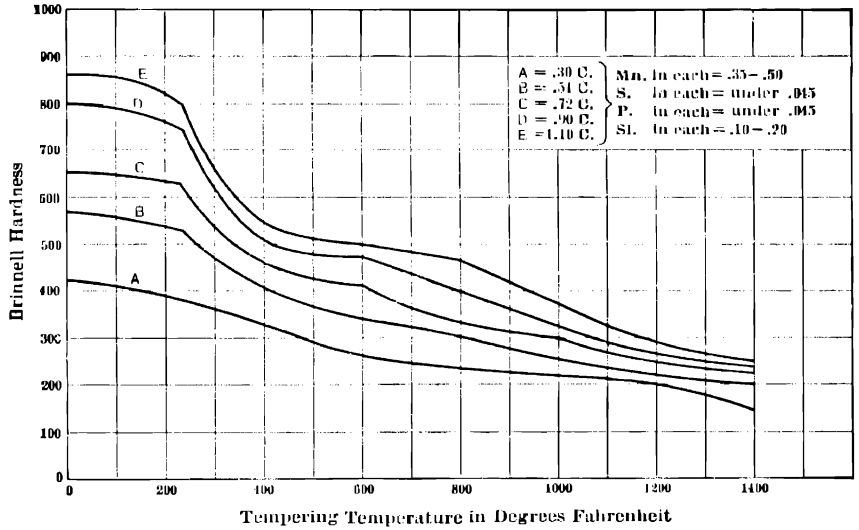

FIG. 27.—Effect of Tempering on the Hardness of Water-quenched Spring Steels. (Tinsley.)

Similar data for small specimens of steel oil quenched and drawn at various temperatures in a bath of sodium and potassium nitrates were secured by Nead in his experiments, see Fig. 28. From a comparison of these curves it becomes evident that water-quenched specimens are much harder than oil-quenched of like composition and size. The extreme hardness of the water-quenched pieces is diminished by very low drawing temperatures whereas the hardness of oil-quenched pieces remains unaffected until the drawing temperature is raised considerably—above 350° C. in Nead's tests.

707. Methods of Tempering or Drawing Steels.—In all heat treatment operations, the aim is to secure a minimum size of grain. The maximum temperature of heating (for hardening) should be held as close as practicable to the critical range. The latter varies somewhat with different steels, and is best determined from cooling-curve data obtained with a pyrometer. For steels of moderate or high-carbon content (above 0.50 C.) loss of magnetism in the heated steel coincides with the critical temperature; thus a magnet serves as a detector, since it will not be attracted by the heated object if the transition zone has been passed.

The drawing temperature is most accurately indicated by a pyrometer; but in tool dressing, color methods give a simple and reasonably accurate control. If a piece of hardened cold steel is brightened and placed in a hot furnace, the surface will assume oxide tints varying through pale straw color, brown and blue to the final blackish scale color, as the temperature of the steel rises; and it will become progressively softer. The approximate relations of temperature and color, both oxide and incandescence, are noted in the accompanying table.

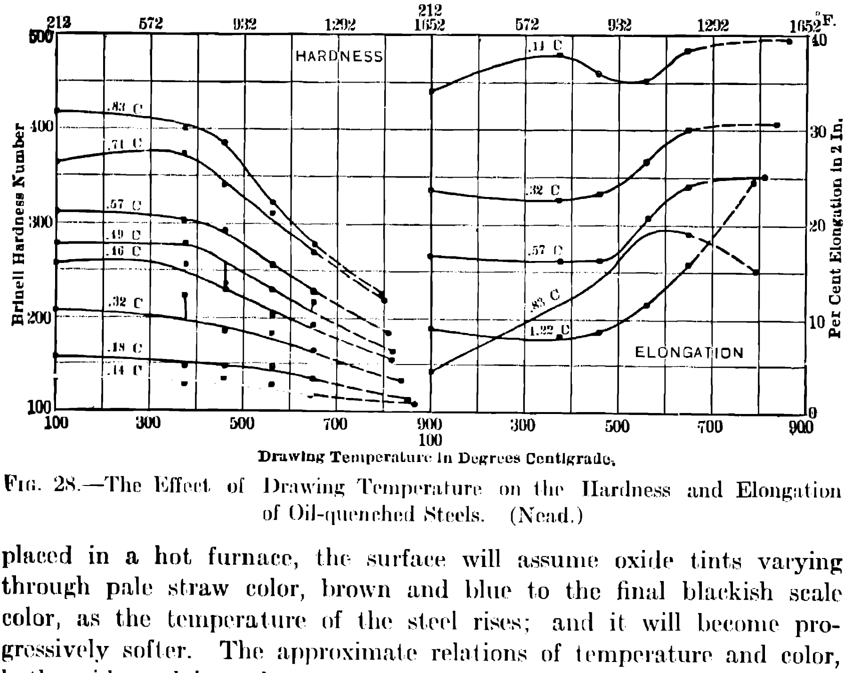

FIG. 28.—The Effect of Drawing Temperature on the Hardness and Elongation of Oil-quenched Steels. (Nead.)

Color of Oxide.	Deg.C.	Deg.F.	Degree of Incandescence.	Deg.C.	Deg.F.
Light straw	221	430	Red—visible in dark	400	752
Straw	232	450	Red—visible in twilight	474	885
Dark straw	243	470	Red—visible in daylight	524	975
Yellow brown	254	490	Red—visible in sunlight	581	1078
Dark brown	266	510	Dull cherry red	800	1472
Brown purple	271	520	Cherry red	900	1652
Dark purple	277	530	Bright red	1000	1832
Bright blue	288	550	Orange yellow	1200	2192
Full blue	293	560	Yellow white	1300	2372
Dark blue	316	600	Welding white	1400	2552

Most tools of ordinary carbon steel are treated by heating to a temperature slightly above the critical range (Fig. 10); the edge of the tool is hardened, by quenching in water or oil, withdrawn from the bath and brightened. The surplus heat in the red-hot unquenched portion is allowed to reheat the hardened quenched part until the proper temper color has reached the edge, the whole tool is then quenched to check further drawing of temper. This method is best for edge tools, such as lathe tools, since it gives the proper hardness at the edge, backed by a softer and tougher portion better adapted to withstand shock. However, it is unsuited for taps, milling cutters, etc., which must have uniform or distributed hardness; in this case quenching of the entire tool and subsequent reheating in the furnace are necessary. To avoid cracking, large sections, such as axles or shafts, should never be quenched to room temperature if they are to be placed in a hot drawing furnace, but should be held at 100 to 150° C. For carbon steels, the initial heat for quenching is preferably carried to the lowest temperature at which hardening will take place, since there will be the accompaniment of minimum coarsening of grain, and resultant maximum toughness of product.

Reheating of the hardened steel parts may be done in a furnace on a hot plate, in a sand bath or in a liquid bath. For drawing temperatures under 300° C. oil is commonly used. For higher tempering temperatures a salt bath made of 2 parts potassium nitrate to 3 parts sodium nitrate or a lead bath is often employed.

Heating of the metal either in hardening or drawing should be at a sufficiently slow rate to secure a uniform temperature throughout the piece.

708. Drawing Temperatures for Various Classes of Steels.—The degree of tempering will vary with the nature of service, being greatest for tools subjected to shock, and where great hardness is less essential than toughness. Stoughton * gives the following drawing temperatures for various classes of tools:

225° C. to 235° C.	Faint Straw to Dark Straw	Tools for metal planers, small turning steel, and wood engraving.
236° C. to 250° C.	Dark Straw to Light Brown	Punches and dies, taps and dies, milling cutters, boring tools, reamers, wood machine tools rock drills.
251° C. to 275° C.	Light Brown to Purple	Twist drills, wood tools.
276° C. to 300° C.	Purple to Blue	Cold chisels, wood chisels, axes, metal and wood saws.

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* *The Metallurgy of Iron and Steel*, p. 384.

Springs are drawn at temperatures between 300 and 450° C. and axles and shafts are toughened by drawing between 400 and 650° C.

709. Carbon Contents for Tool Steels.—Plain tool steels have a carbon content varying with the service requirements. United States Navy specifications (L. H. Kemmey, Soc. Nav. Arch. and Mar. Engrs.) are as follows:

	Class 1.	Class 2.	Class 3.	Class 4.
Carbon	1.25–1.15	1.15–1.05	0.95–0.85	0.85–0.75
Manganese	0.35–0.15	0.35–0.15	0.35–0.15	0.35–0.15
Phosphorus	0.015	0.015	0.020	0.020 max.
Silicon	0.40–0.10	0.40–0.10	0.40–0.10	0.40–0.10
Sulphur	0.020	0.020	0.020	0.025 max.

Vanadium and chromium optional.

Class 1—Lathe and planer tools, and tools requiring a keen cutting edge combined with great hardness; drills, taps, reamers and screw-cutting dies.

Class 2—Milling cutters, mandrels, trimmer dies, threading dies, and general machine-shop tools, requiring a keen cutting edge combined with hardness.

Class 3.—Pneumatic chisels, punches, shear blades, etc., and in general tools requiring hard surface with considerable tenacity.

Class 4.—Rivet sets, hammer, cupping tools, smith tools, hot drop forge dies, etc., and, in general, tools which require great toughness combined with the necessary hardness.

710. Surface Hardening Methods.—Certain steel parts such as armor plate, safes, plowshares, special types of gears, pinions, and bearing surfaces must combine toughness with a high resistance to indentation or abrasion. Large surfaces, as in safes, armor plate and plowshares, are made by sandwiching tough soft steel plates between hard plates and rolling the combination together at a welding heat. Then the exterior plates are heat-treated to secure the desired hardness and toughness.

Case hardening consists in forming a hard surface on a wrought iron, malleable cast iron, or low-carbon steel, part by heating above the critical range (900–950° C.) while surrounded by a medium rich in carbon. The surface metal should not contain initially over 0.2 per cent carbon. For a heavy case the metal is held at the high temperature 1 to 8 hours. After the required case has been formed, the parts may be heat-treated in several ways. If a hard surface is wanted and toughness is of small moment, the objects may be withdrawn from the furnace and immediately plunged into cold water or oil. Such treatment will result in a hard case but both case and core will be coarsely crystalline. If toughness is important, the objects should be cooled below the critical range, then heated above the upper critical point for the core (900° C.), and quenched. This procedure hardens and refines the grain in the core but makes the case coarse-grained.

By reheating to a temperature just above the critical range of the case (775 to 825° C.) and again plunging in water or oil the core will be annealed, the case hardened, and its grain refined.

Manganese, tungsten, chromium, and molybdenum steels are readily case-hardened; but those of nickel, silicon, and aluminum are less susceptible.

Among the substances used for packing materials are granulated bone, wood charcoal, burnt leather, a mixture of 2 parts barium carbonate to 3 parts wood charcoal, potassium cyanide, and gases rich in carbon monoxide, such as illuminating gas. Granulated bone is the base of most of the packings used in this country. Although the rate of penetration of carbon is slower with wood charcoal than with burnt leather or the barium carbonate and charcoal mixture, yet it gives good satisfaction when a deep case is required. The potassium cyanide compounds quickly produce thin uniform cases, but evolve poisonous gases which render them dangerous.

The thickness of the case varies from 0.02 to 0.2. Ordinarily the case wanted is less than 0.1 in. thick. Best results are obtained when the carbon content of the case is slightly above the eutectoid ratio (0.9 to 1.0 per cent). There is very little absorption of carbon when the temperature is held below Ac_1. Above that point the rate of penetration increases with the temperature and decreases with the time of exposure.

Nitriding of certain steels will produce a case hard enough to scratch glass (900–1100 Brinell) and high in resistance to atmospheric corrosion. The operation is conducted on steels containing appreciable percentages of aluminum, vanadium, or nickel combined with chromium or molybdenum. Parts to be nitrided are loosely packed in gas-tight boxes, which are heated, under careful control, between 500 and 600° C. While thus heated, ammonia gas is circulated through the boxes for 2 to 90 hr. Parts are then slowly cooled in the furnace. The case depth is usually less than 0.03 in. (see *Trans. Am. Soc. Steel Treating*, Vol. 16, No. 5, 1929).

Two useful developments in methods of heating surfaces are provided by *flame hardening* and *induction hardening*. In the former the oxyacetylene torch is used to heat the surface and quenching is accomplished by application of water spray or compressed air. Induction hardening is most readily applied to cylindrical surfaces like crank shafts. It is accomplished by sending a high frequency current with high amperage and low voltage through inductor blocks which surround but do not contact the object to be hardened. These blocks, acting like the primary coil of a transformer, induce a current in the object which is thus quickly heated through hysteresis and eddy current losses. Quenching is done by a water spray passed through the inductor blocks.

711. The Influence of Hardening and Tempering on Mechanical Properties.—The great influence exerted by carbon on the capacity of steel for hardening by heat treatment has been pointed out. Besides increasing hardness, quenching of medium- and high-carbon steels raises both the strength and elastic limit and lowers the ductility of these steels.

By hardening and tempering, or by cooling less rapidly through the critical zone, a wide range in physical properties can be obtained. Of these methods hardening and tempering provides the better control of the properties of the treated object.

Brinell's Strength Tests. The data furnished by Brinell's * experiments provide some good illustrations of characteristic influences of various heat treatments on the mechanical properties of steels. Some of his data have been plotted in Fig. 29, 30, and 33. From Fig. 29 and 30 it follows that water quenching from above the critical zone without subsequent drawing causes an increase in the strength and a loss in the ductility of the low- and medium-carbon steels and for these steels is more effective than oil quenching. (It should be borne in mind, however, that such quenching when applied to larger pieces of steel is likely to produce heavy internal stress and may even cause cracking.) For the high-carbon steels the oil-quenching treatments gave greater strength and ductility than quenching in water at corresponding temperatures. Water quenching of the high-carbon steels caused warping and heavy internal stress. Under such conditions the specimens were eccentrically loaded in testing and, being very brittle, broke at comparatively low stresses. In Brinell's quenching and drawing treatments it appears that drawing at 250° C. after quenching in oil at 80° C. had about the same effect on strength and ductility as quenching in water at 20° C. and tempering at 550° C.

Quenching from 850° C. followed by tempering gave the best combination of strength and ductility of the treatments tried by Brinell. This is especially true for the water-quenched specimens. It is likely that quenching the high-carbon steels at a somewhat lower temperature and the low-carbon steels at a somewhat higher temperature could have given still better results. It will be observed that in the case of water-quenched specimens the drawing temperature necessary to give the greatest strength increases with the carbon content. For example, consider the plotted data in Fig. 29 for steels water-quenched from 850° C. The 0.09 per cent carbon steel was strongest when quenched, the 0.25 and 0.44 per cent carbon steels were strongest when drawn at 350° C., and the other steels had highest strength when drawn at 550° C. It is likely that high-carbon steels would have had still greater strength if drawn at 400 or 450° C.

The influence of tempering on the strength and ductility of oil-quenched steels is well brought out by the results of Nead's tests.† In these experiments quenching was done at temperatures slightly above those recommended by the Am. Soc. for Metals (see Fig. 10), and the results are very uniform. In Fig. 31 it will be observed that the ultimate strength and yield point are not materially affected by tempering at temperatures under 400° C. Fig. 28 shows that the ductility, excepting the 0.83 per cent carbon steel, is also unaffected by tempering within this range. There is produced, however, a marked decrease in strength and elastic limit and a corresponding increase in ductility as the drawing temperature is raised above 400° C. These effects are most pro-

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* *Jour. of Ir. and St. Inst.*, 1901, Pt. 2, p. 234.

† *Trans. Am. Inst. of Min. Eng.*, Vol. 53, p. 218.

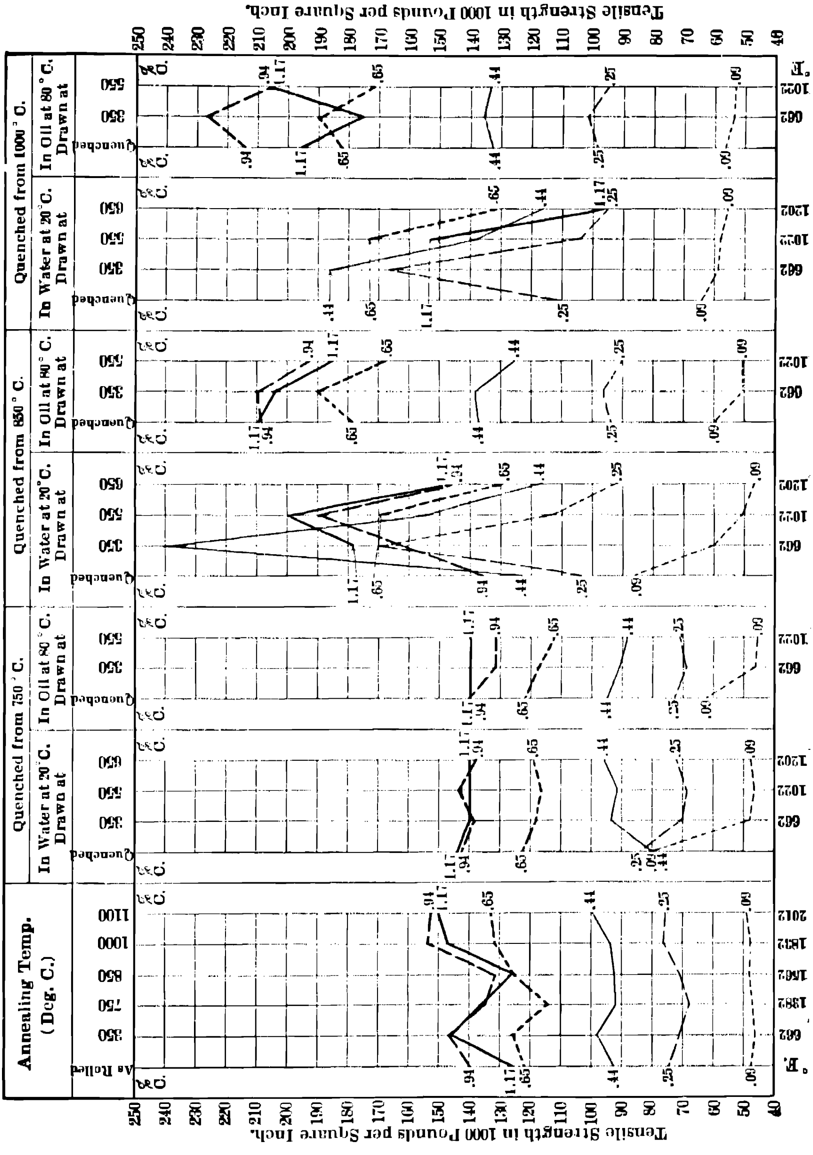

FIG. 29.—The Effects of Various Heat Treatments on the Tensile Strength of Acid Open-hearth Steels. (Brinell.) In most cases each point represents a single test. Specimens were 0.71 in. in diam. Composition limits were Si = 0.005–0.313, Mn = 0.10–0.49, S = 0.012–0.020, P = 0.0250–.029.

nounced in the high-carbon steels, as would be expected. For larger pieces strength and ductility would be less affected by quenching, and constant for a greater range in drawing temperature.

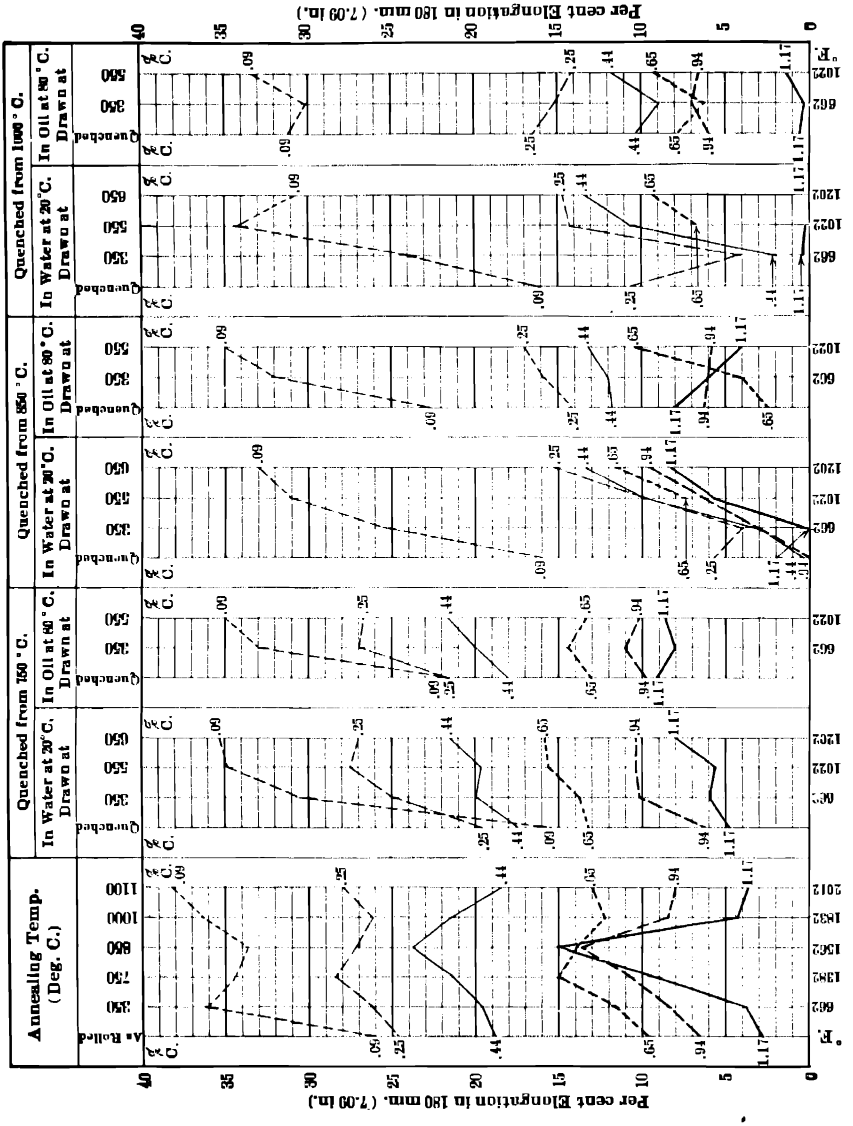

FIG. 30.—The Effect of Various Heat Treatments on the Elongation of Acid Open-hearth Steels. (Brinell.)

The toughening effect of quenching followed by drawing at various temperatures is admirably illustrated by the tests of Grard * which are summarized in Fig. 32. The curves for energy of rupture in impact show that the low-carbon steels are the toughest and that maximum toughness in each of the steels tested was produced by drawing at a temperature about 50° C. below the upper critical point (Ar_3).

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* *Proc. I. A. T. M.*, 1912, III_2.

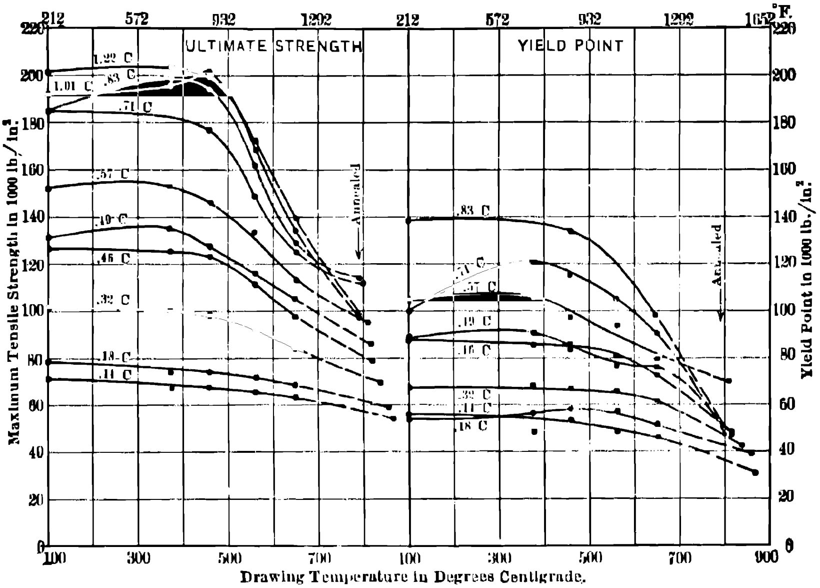

FIG. 31.—The Effect of Drawing Temperature on the Strength of Oil-quenched Steels. (Nead.)

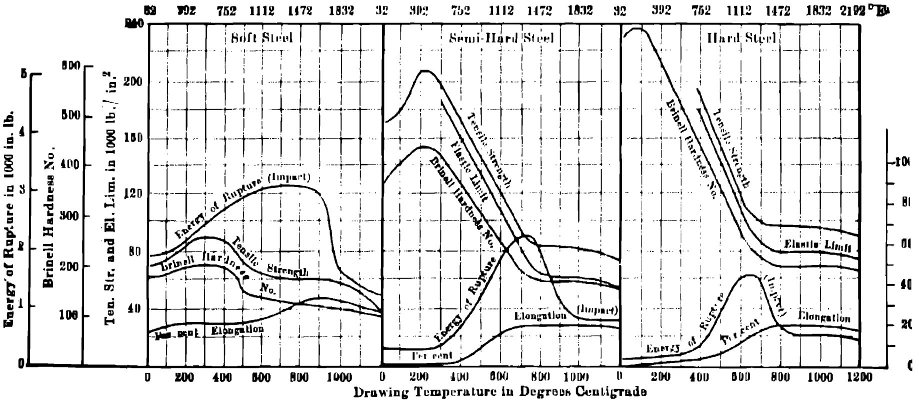

FIG. 32.—Effects of Drawing Temperature on the Mechanical Properties of Three Grades of Steel. (Grard.) Impact tests were made on notched specimens.

For drawing temperatures below 400° C. the energy of rupture of the semi-hard and hard steels is low and constant. Again when the annealing temperatures are reached in the drawing process the toughness abruptly decreases. It appears, therefore, that the quenched steels in the martensitic state, and those which have been tempered into a troostitic state are very strong and hard but they do not possess the toughness of the sorbitic steels formed by drawing at higher temperatures (500° to 700° C.). Furthermore, the pearlitic steels formed on annealing after quenching, although more ductile, have less shock resistance than those in the sorbitic state.

Results of some of Brinell's impact tests have been plotted in Fig. 33 (*b*) and (*c*). These also indicate the superior resistance of low-carbon steels under impact and show that the medium and high-carbon steels are materially improved by quenching and drawing at a high temperature. They do not show, however, that such treatment is so beneficial for the low-carbon steels.

By comparing Fig. 33 (*a*) with Fig. 33 (*b*) and (*c*) it becomes evident that the energy of rupture computed from tension tests is not a

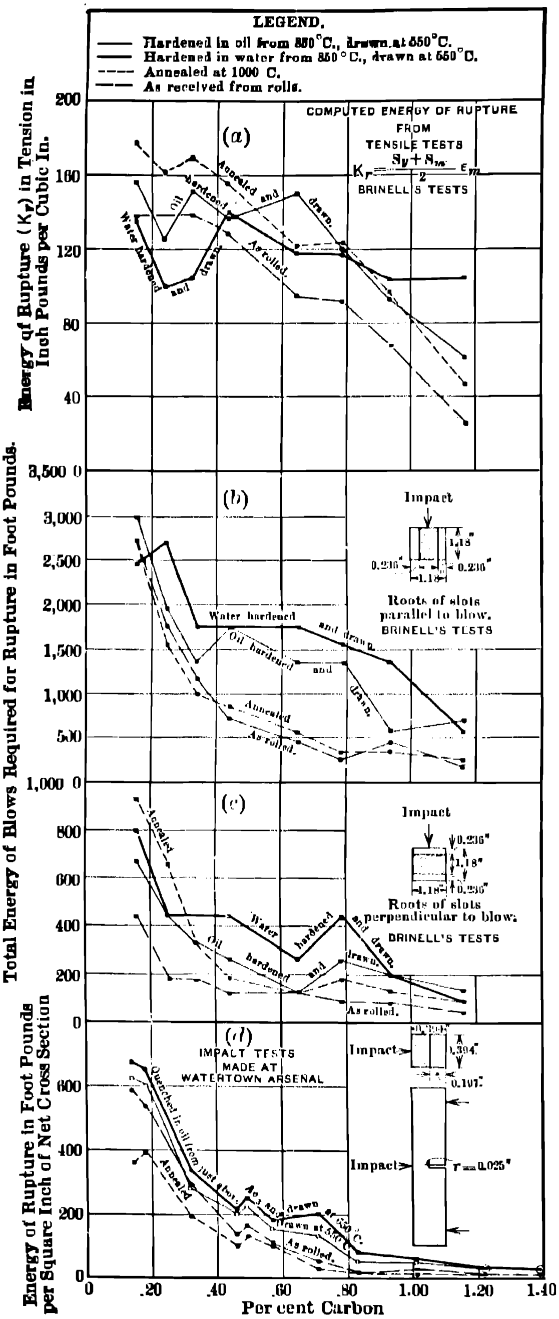

FIG. 33.—The Influence of Carbon on the Toughness of Steel as Measured by the Energy of Rupture in Tensile Tests and in Impact Tests.

measure of the efficiency of a heat treatment in toughening steels. In other words the efficiency of a toughening treatment should be judged by the results of impact tests. In general the nicked impact test with the blow applied normal to the root of the nick is the most severe type of test for such purpose.

In Fig. 33 (*d*) are plotted results of Charpy impact tests made on the same steels as used by Nead (see Fig. 31). The results are more consistent than those of Brinell and, likewise, show the beneficial effects of drawing oil-quenched steels at 650° C., thus producing a fine-grained sorbitic structure giving maximum toughness.

EFFECTS OF MECHANICAL WORK

712. Effect of Hot Work on Structure.—The mechanical working of steel may be hot or cold; it may be carried out at temperatures above or below the transition zone. In heating steel above the critical temperature, there is a complete obliteration of existing grain, and a progressive increase in grain size of the newly formed austenite with temperature rise above the critical range, and with time intervals which will allow of normal crystallization. Symmetry of crystallization is the tendency in the austenitic zone, and the size and character of grain thus attained is not destroyed during the reverse transition in cooling to normal temperature.

Mechanical work results in distortion of the grains causing flattening in the direction of the pressure and consequent destruction of the normal symmetry. Within the austenitic range the metal will split up into a mass of grains of symmetrical character, and approximately of the dimensions determined by the distortion; these will in turn grow into an aggregate of larger symmetrical grains conforming to the temperature and time conditions. If, therefore, as is usual in mechanical work operations, distortion and reduction of grain size within the austenitic temperature range is accompanied by a gradual decrease of temperature of the metal, the resultant grain must be finer than the original, since there has been mechanical reduction, accompanied by a lower end temperature which will largely determine the size of the final grain. This size will be a function of the amount of reduction of the initial grain by the mechanical operations, and the finishing temperature as compared with the critical. Heavy reductions will tend to result in a fine-grained structure; this in turn will tend to increase in size the higher the finishing temperature is above the critical one, and the more the time approaches that needed for complete aggregation. From the standpoint of the doctrine of grain size—that strength and ductility are the accompaniment of fineness of structure—

the importance of hot work in improving the physical quality of steel is obvious, and it is especially beneficial if the reductions are heavy and at finishing temperatures as close as practicable to the critical zone. A comparison of Figs. 11 and 12 shows the marked improvement in refining the grain which has been accomplished by forging a piece of cast steel.

The specifications of the United States Navy for steel forgings demand that the diameter of the grains in the finished part, as determined under the microscope, shall not exceed 0.005 in.

713. Effects of Hot Work on Properties of Steel and Iron.—It is evident that the rate of cooling of a steel section will have an important influence upon the structure and physical properties, provided the mechanical work is finished at a temperature above the critical range. That is, in addition to the direct effect of mechanical refining of the grain, there is the accompaniment of the effects of hardening and tempering, because of direct treatment or the equivalent result due to natural cooling conditions. The tempering effects conform to the principles set forth heretofore, and are proportionately greater in high-carbon or special-alloy steels than in the mild steels which are of greatest importance in usual construction. The best results are obtained by the proper correlation of mechanical work and heat treatment of a steel of suitable chemical composition, all determined by consideration of the service conditions. A few examples illustrating the effects of hot working follow.

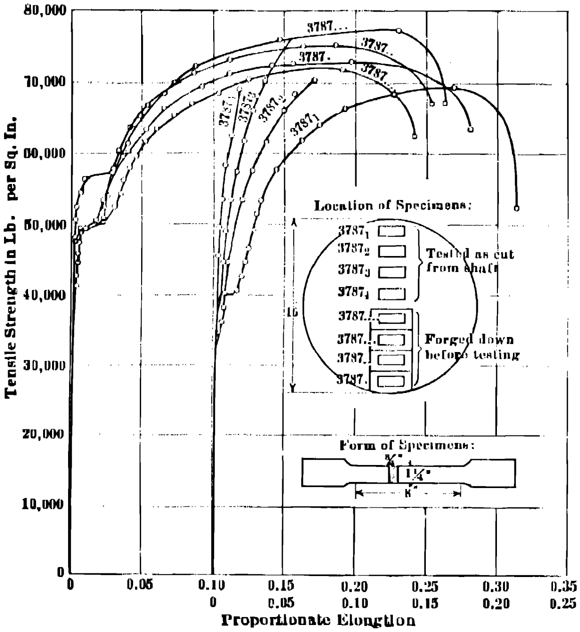

FIG. 34.—Showing the Varying Character of Metal in Different Parts of the Cross-section of a Large Steel Shaft when Forged under a Ten-ton Hammer. (*Tests of Metals*, 1885.)

In Fig. 34 is shown the cross-section of a steel shaft 16 in. in diameter (which broke soon after being put in service) from which eight test-specimens were cut, lying symmetrically in a diametral section as shown. Four of these were tested as cut from the shaft. The other four were forged down after cutting out. The plotted results show: The elongation of the unforged specimens varied from 21 per cent in the specimen taken from near the surface of the shaft to 2 per cent in the specimen coming from near the center. In the forged specimens, however, taken from the opposite side of the disc, the elongation varied from 28 per cent near the surface of the shaft to 24 per cent near the center, thus showing that the material was identical throughout when it had been similarly worked. In other words, the material near the center of the shaft was in its primitive condition when first cast, while that near the surface was that of well-rolled steel. This shows the necessity of forging large shafts under enormously heavy hammers, or, better, the necessity of using only hollow-forged shafts for such service.

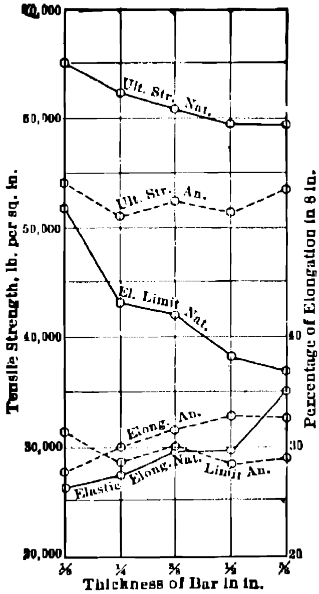

FIG. 35.—Effect of Thickness on the Mechanical Properties of Mild Steel, Natural and Annealed. (*Campbell's M'f'g and Prop. of Iron and Steel.*)

The amount of reduction which a piece receives in rolling materially influences the mechanical properties. Bullens * cites tests of bars ranging from $\frac{1}{2}$ in. to 3 in. in diameter all rolled from the same ingot. The tensile strengths of these bars varied from 137,000 to 100,000 lb. per square inch, respectively.

In Fig. 35 the characteristic influence of thickness on the properties of mild steel bars is well shown. It will be observed that the strength and elastic ratio decrease slightly but the ductility increases as the thickness of the metal is increased. Annealing greatly reduces these effects.

From Fig. 36 it may be seen that the variation in ultimate strength and in the elastic limit for various thicknesses of metal is much greater when the metal leaves the rolls at a dull red heat. Working at this temperature slightly increases the ultimate strength and ductility and raises the elastic limit from 8 to 10 per cent above the values gotten at normal finishing temperatures (a bright red). After annealing, Campbell's tests show that specimens finished at a dull red heat still have properties superior to normal specimens similarly annealed.

In general the apparent elastic limit rises as the thickness of section diminishes. Since steel columns are built from comparatively thin sections of metal (generally from ¼ to ½ in. in thickness), and since the ultimate strength of these is dependent wholly on the apparent elastic limit, and not at all upon the ultimate strength, it is necessary to evaluate this elastic limit for the particular thicknesses of sections used, rather than from special test bars, which are usually not less than ¾ in. in thickness.

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* *Steel and Its Heat Treatment,* p. 229.

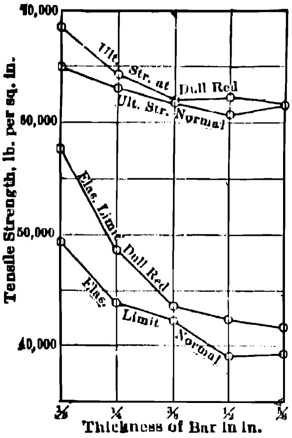

Fig. 36.—Influence of Thickness on Mechanical Properties when the Percentage of Reduction in Rolling is Constant, Last Passage in Rolls being at Normal and Dull Red Heat, Respectively. (Campbell's *Manufacture and Properties of Iron and Steel.*)

Differences in the amount and character of work which various parts of a steel shape receive during rolling often cause considerable discrepancies in mechanical properties. From Fig. 3, Ch. XIX, it will be noted that the material near the center of the web and in outer portions of the flanges of an I-beam is worked more in rolling than the portions at the junction of the flange and web. Results in Table 5 show variations in the properties of test-pieces cut from these parts of several I-beams.*

714. Methods of Cold Working.—Cold working of steel, or reduction of area at temperatures well below the critical zone, results in distortion of the grain in accordance with the applied forces, and this distortion remains because of lack of mobility or tendency to acquire symmetry at temperatures much below the critical, Fig. 37. Cold distortion causes increased density and produces an internally strained condition in the steel. It is accompanied by increased hardness, tensile strength, and, if a period of rest is allowed, by an increase in elastic limit.† The ductility and shock resistance, however, are lowered by cold working. Cold drawing, cold rolling, cold pressing (or flanging), and cold twisting are the usual methods of cold working metals. The drawing and rolling processes are very effective in securing parts of exact cross-sectional dimensions. The cold-drawing process is used mostly on pieces of small cross-sectional area,—such as wire, automatic screw stock, small shafting and tubing,—where a large reduction in area can be made in a single draft. For large shafts and axles cold rolling is more efficient than cold drawing. Cold rolling impairs the ductility of the metal less than cold drawing, probably

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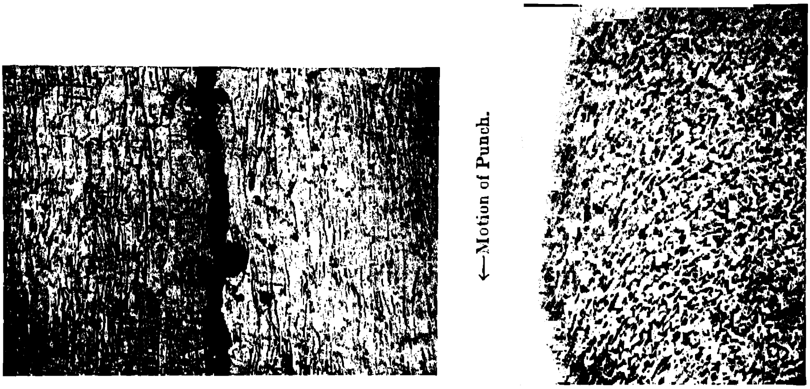
* From the carefully conducted tests of E. L. Hancock, *Proc. A. S. T. M.*, Vol. 10, p. 248.

† Elastic limit is used synonymously with proportional limit in Arts. 714 to 717.



(a) The distortion is much less in the hot-rolled metal (7) than in the cold-rolled (8).

(b) Distortion due to cold punching. Hole at left.

FIG. 37.—Distortion Due to Cold Work. (Mag. = 50d.)

TABLE 5.—TENSION TESTS OF STEEL SPECIMENS CUT FROM I-BEAMS (HANCOCK).

The specimens were taken from the center of the web, from the flange near the web, and from the root of flange and web. Elastic limit was determined by an extensometer reading to 0.0001 inch.

Depth of Beam (in.).	Weight per Foot (lb.).	Elastic Limit (lb./in.^{2})			Maximum Strength (lb./in.^{2}).			Per Cent Elongation in 8 In.		
		Web.	Flange.	Root.	Web.	Flange.	Root.	Web.	Flange.	Root.
Standard Beams										
6	13.5	32,000	34,000	34,000	68,300	65,300	64,300	18.7	29	29
10	25	30,000	25,500	33,000	56,500	54,600	58,600	28.3	28.1	25
10	25	24,750	26,600	27,000	72,300	61,200	66,400	20.2	34.4	25
12	31.5	29,500	22,500	19,500	61,800	59,500	63,700	31.3	26.6	25
12	40	31,500	21,000	19,500	59,800	62,500	61,500	31.2	21.9	31.2
12	40	28,500	18,700	24,000	62,200	62,200	61,700	30	18.7	31
15	42	31,500	29,900	22,500	68,790	.....	56,000	28.2	....	26.6
15	60	19,500	24,000	16,500	53,300	55,200	53,800	29	29	29
15	80	27,000	19,500	19,500	54,300	55,300	55,000	36	31	33
18	55	31,500	25,500	19,500	55,800	56,700	60,400	28.5	29	28.5
20	65	34,500	22,500	13,500	62,700	63,800	64,000	28.5	28	30
Bethlehem H-Beams										
24	73	33,000	24,000	22,500	72,600	70,000	67,300	25	28	28.1
18	48.5	19,500	21,000	28,500	59,600	57,300	56,200	26.6	31.3	31.3
12	36	31,500	33,000	24,000	72,600	66,000	68,400	21.9	26.6	25
Mean Values		28,875	25,050	23,107	62,893	60,738	61,236	27.39	27.82	28.40
Based on Web		1.00	.865	.800	1.00	.965	.974	1.00	1.018	1.039

because the total reduction in area is effected by a large number of light passes through the rolls. The reductions in either of these processes are very much less than in rolling or drawing hot. Cold pressing is much used in fashioning thin parts in car construction, and in making of sheet metal forms. Cold-pressed parts which must withstand shock require annealing. Cold twisting is used to raise the elastic limit and ultimate strength of square steel bars for reinforcing concrete.

Cold punching of holes in boiler plate, in structural steel and forms made of wrought iron and soft steel is very commonly practiced. The method is rapid and cheap but causes heavy distortion in the vicinity of the holes as shown in Fig. 37*b*. Since the metal on the die side of the hole is considerably embrittled by this process (see Fig. 16, Ch. III), and is also rendered more susceptible to corrosion (see Fig. 1, Ch. XXIX), good practice demands that the holes be punched about ⅛ in. undersize and reamed to required dimensions.

716. Effects of Cold Work on Properties.—Tests on hot-rolled and cold-rolled shafting by Thurston at Cornell University* show that cold rolling increases the elastic limit in tension from 15 to 97 per cent, the tensile strength from 20 to 45 per cent. Under cross bending the elastic limit is raised 11 to 30 per cent and the yield point 13 to 69 per cent. The elastic limit in torsion is raised from 28 to 40 per cent. That the effect of cold rolling on the strength penetrates undiminished to the axis of the bar is demonstrated by a portion of Thurston's results, given in Table 6. The ductility of the metal at the surface is greater than that at the center but the discrepancy is most marked in the cold-rolled metal. In elastic resilience the cold-rolled metal is superior to the hot-rolled; in energy of rupture it is inferior to the hot-rolled metal. The modulus of elasticity is slightly increased by cold rolling, in these tests by about 1,000,000 lb. per square inch.

From a series of tests by A. J. Wood† on cold-drawn steels of low-carbon content the following conclusions seem justified. Cold drawing by reducing the diameter about $\frac{1}{16}$ in. in one draft increases the maximum strength of bars less than 1½ in. in diameter about 10 to 15 per cent. It increases the elastic limit about 100 per cent, reduces the elongation by 75 per cent and the reduction in area by about 15 per cent. Cold drawing raises the strength and elastic limit both by direct stretching of the metal and by lateral compression which also causes lengthening of the piece. The properties of the metal are approximately uniform throughout the piece.

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* See abstract in *Machinery*, April, 1917.

† *Engr. News*, Vol. 59, p. 63.

TABLE 6.—RESULTS OF TESTS ON COLD-ROLLED AND HOT-ROLLED STEEL BARS.

Diameter of Bar in Inches.	Stress in Pounds per Square Inch.				Elongation in 8 In. in Per cent.	Reduction of Area in Per cent.	Resilience in Inch Pounds per Cubic Inch.		Modulus of Elasticity in 1000 Lb. per Square Inch.
	Elastic Limit.	Yield Point.	Maximum.	Breaking.			Elastic Limit.	Breaking.	
				Cold-rolled Steel					
0.349	54,000	62,500	73,637	51,613	7.50	53.70	48.14	5,600	30,393
0.526	59,500	66,000	75,739	55,060	10.12	54.10	56.21	7,340	31,560
0.772	53,500	66,000	76,636	54,548	12.31	55.70	47.02	9,000	30,476
1.019	52,000	62,000	73,778	50,205	14.87	57.80	42.25	10,480	30,056
				Hot-rolled Steel					
0.355	30,000	35,250	58,606	40,164	22.06	68.0	15.32	10,900	29,418
0.509	31,900	35,500	58,809	41,569	24.31	61.7	17.51	12,860	29,073
0.754	29,750	35,750	59,747	41,793	29.25	64.2	15.67	15,280	28,337
1.010	30,250	35,250	61,210	43,392	30.00	63.8	14.43	16,740	29,126

In the above tests by Thurston and by Wood the properties were determined from pieces turned down to various proportions of the original diameter of the rolled section, but no direct measurements of the relief of internal stress due to the machining are reported. From the experiments of Heyn * and others, however, it seems certain that cold-worked metals, especially those which are cold drawn, are liable to severe internal stress. In a cold-drawn piece the core is placed under compression and the outer layers under tension. Thus, in one of the Heyn tests on a steel bar (Ni = 25, C = 0.3 per cent) which was reduced in diameter from 1.34 to 1.22 in. by cold drawing, the maximum tensile stress near the surface of the bar was 50,000 lb. per square inch and the maximum compressive stress along the axis amounted to 54,000 lb. per square inch. By annealing at 850° C. the maximum internal stress was made less than 3500 lb. per square inch. Heyn also cites instances of failures of cold-drawn parts of steel and brass caused by internal stress.

From the foregoing it appears that a material increase in elastic limit and ultimate strength of steel with a corresponding loss in ductility and toughness may be secured by light reductions in cold draw-

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* *The Jour. Inst. of Metals*, Vol. 12, p. 12.

ing, but if the reductions are large the internal stresses thus induced may adversely effect the strength as well as toughness and ductility.

The effects of cold twisting on the strength and ductility of mild steel bars is illustrated in Fig. 38.* The elastic limit in these tests was increased from 10.5 per cent for the $\frac{3}{8}$-in. bars twisted one turn in 12d to 80.5 per cent for the $\frac{5}{8}$-in. bars twisted 3¼ turns in 12d. For manufacturing twisted reinforcing bars one turn in a length of 6 to 12 diameters is commonly used. In a paper before the A. S. T. M, J. J. Shuman, a manufacturer, advocated 1 twist in 8 to 10 diameters for Bessemer steel of 60,000 lb. per square inch tenacity and 1 turn in 5 to 7 diameters for basic open-hearth material of like strength. The data in Fig. 38 indicate that twisting a bar of mild steel through one turn in 8 diameters causes an increase in strength of 13 to 22 per cent but produces a decrease of 50 to 70 per cent in elongation. Under such treatment the elastic limit will be raised 40 to 60 per cent.

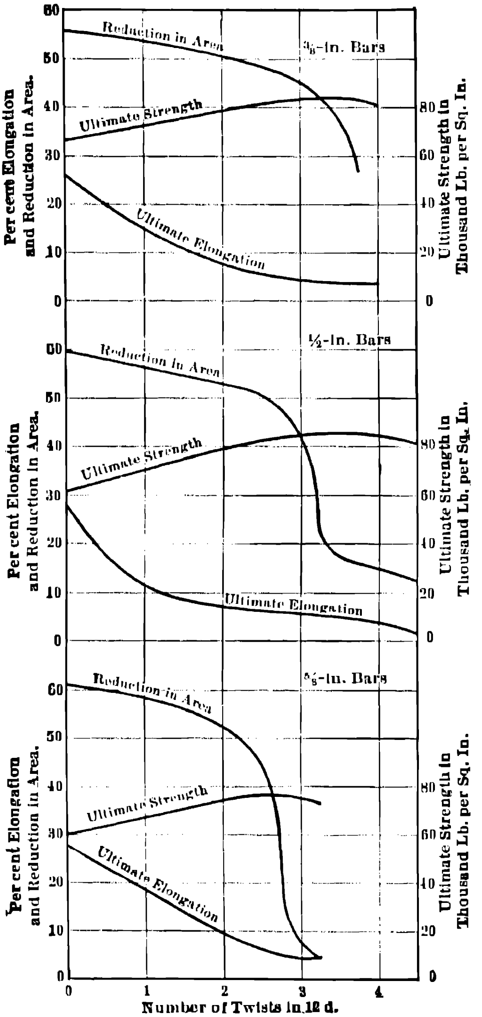

FIG. 38.—The Effect of Cold Twisting on the Strength and Ductility of Mild Steel Bars. (Whitney and Dohner.)

It becomes apparent that cold twisting produces a large increase in elastic ratio and a considerable increase in strength. These changes are accompanied by a marked reduction in ductility and a probable loss in shock resistance.

716. Relief of Distortion Due to Cold Working.—In wire drawing, several passes through the dies makes the steel so brittle that annealing is necessary to restore ductility and ensure further reduction without rupture.

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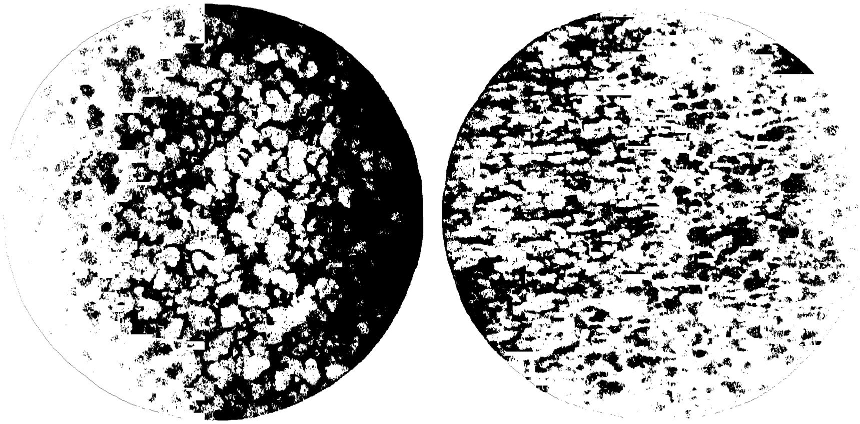
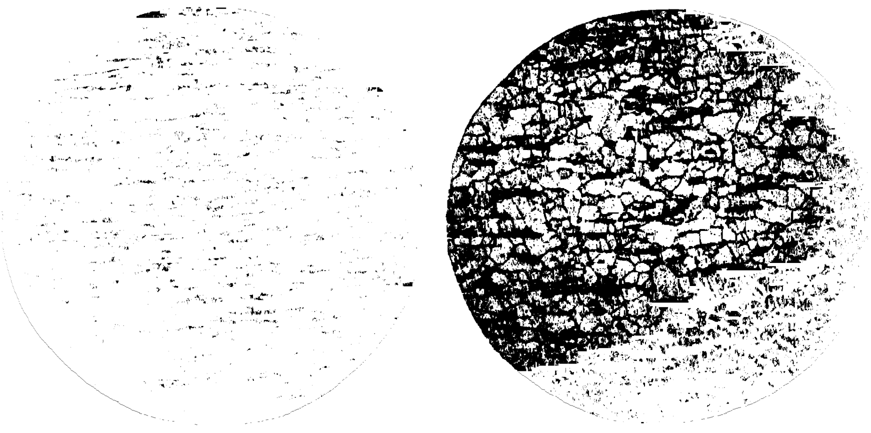
* Abstract in *Jour. Am. Soc. M. E.*, Dec., 1916, of tests by Whitney and Dohner at University of Colorado.

It is usually considered that temperatures above the critical are necessary to remove the distortion of structure due to cold work.



(*a*) Steel rod annealed.

(*b*) Steel wire after one draft. Area of rod reduced 15%.



(*c*) Steel wire after several drafts. Area of rod reduced 60%.

(*d*) Steel wire hard-drawn and then annealed at a temperature below critical range.

FIG. 39.—Effects of Drawing and Annealing on the Structure of Soft Steel Wire (0.08% C.). Magnification 95 diameters. (J. F. Tinsley.)

However, in the manufacture of wire, the annealing temperatures (process annealing) are approximately 600° C. or well below the Ac_1 point. That there is effective removal of grain distortion and restoration of ductility is indicated by Figs. 39*a* to 39*c* and Table 7, representing typical practice in the drawing and annealing of mild steel wire of 0.10 per cent carbon content. (J. F. Tinsley before Am. Ir. and St. Inst., May, 1914).

Corresponding results in drawing and patenting 0.50 carbon steel wire are given in Table 8. The patenting operation consists in drawing the wire through a heated tube, at a speed and temperature regulated according to the carbon content and size of the rod and wire; then cooling it in the air or in a bath of molten lead, depending upon the final structure and properties desired. The process is in effect one of combined annealing and tempering, and serves to obliterate the distortions of drawing and to give to the finished product the required combination of strength and toughness, mainly by preventing coarse

TABLE 7.—THE EFFECT OF COLD DRAWING AND ANNEALING ON THE PHYSICAL PROPERTIES OF 0.10% CARBON STEEL. (TINSLEY)

Condition of Material.	Per cent Reduced in Drawing.	Tensile Strength lb./in.²	Per cent Elongation in 10 in.
Green Rod...... No. 5 gage, $d = .207$ in.	0	68,000	25
First draft......	47	113,000	2½
Third draft.....	82	150,000	1½
Process annealed	0	60,000	30
First draft......	35	93,000	3
Third draft.....	70	130,000	2
Fifth draft......	85	145,000	1½
Process annealed	0	62,500	28
First draft......	21	82,000	3½
Third draft.....	62	124,000	2
Fifth draft.....	80½	143,000	1½
Seventh draft...	88½	151,500	1
Annealed.......	0	68,000	25
Dead soft annealed after first and second annealings	....	50,000	32

TABLE 8.—THE EFFECT OF COLD DRAWING AND PATENTING ON THE PHYSICAL PROPERTIES OF 0.50% CARBON STEEL. (TINSLEY)

Condition of Material.	Per cent Reduced in Drawing.	Tensile Strength lb./in.²	Per cent Elongation in 10 in.
Green Rod...... No. 5 gage, $d = .207$ in.	0	95,000	10.0
First draft......	28½	122,000	2.9
Second draft....	51	146,000	2.8
Patented.......	0	115,000	8.2
First draft......	30	143,000	2.8
Third draft.....	50½	163,000	2.7
Fourth draft....	65	176,000	2.6
Patented.......	0	128,000	7.8
First draft......	30	156,000	2.0
Third draft.....	66	190,000	1.9
Fourth draft....	76	208,000	1.8
Patented.......	0	156,000	6.0
First draft......	30	184,000	2.0
Third draft.....	66	218,000	1.9
Annealed after first patenting.	....	70,000	18.0

coalescence of the pearlitic constituents. It is chiefly adapted to medium- or high-carbon steel products such as piano wire or wire for rope strands.

717. Effects of Overstrain in General.—The various methods of cold working, previously discussed, all stress the metal beyond its elastic limit and each produces a particular kind of overstrain. In a general way it has been shown that overstraining a bar in a certain direction, say in tension, will raise the yield point to the overstraining load and will slightly increase the ultimate strength. The magnitude of the effect on the ultimate will depend upon the amount of overstrain. The limit of proportionality is greatly lowered immediately after overstrain.* There is, however, more or less complete recovery as time elapses, and the proportional limit may be eventually raised above the normal value. If the overstrained bar is put under the opposite kind of stress (compression) the yield point and proportional limit of the bar are lowered, they may even vanish if the period of rest after overstrain is small. (See Fig. 6, Ch. XXII.) There is also evidence to show that the effects of overstrain are felt in all directions. Howe † has shown that the ball hardness of a tensilely overstrained steel bar is increased in all directions, in other words, that the effects of simple overstrain are isotropic in hardening the metal. Evidence of influence of overstrain in directions inclined to the overstrain axis is also afforded by Table 9.

From these results it appears that the effect of tensile overstrain on tensile properties is greatest in the direction of the overstrain and least at right angles to it. On the other hand, tensile overstrain effects the greatest increase in compressive elastic limit and strength in directions normal to the overstrain. (See also Art. 671.)

718. Grain Growth in Overstrained Metal.—When a pure metal or alloy of solid solubility is heated subsequent to overstrain a growth in the grain may be produced at temperatures below the critical range. Thus very low-carbon steel, or ingot iron, exhibits a decided growth of its crystal grains after overstrain, on heating to a temperature which varies inversely with the magnitude of the overstrain. For example, McAdam ‡ in experimenting on ingot iron containing 0.034 per cent carbon found that this metal when reduced 30 per cent in thickness began to recrystallize when heated for 8½ hours at 900° F. (482° C.), when reduced 15 per cent crystallization commenced at 1000° F., and when reduced 10 per cent crystallization began at 1100° F. In no case, however, did coalescence of grains take place in the recrystallized material until the temperature of annealing was raised above 1475° F. (801° C.).

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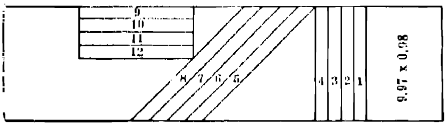
* See *Tests of Metals*, 1915, p. 127.

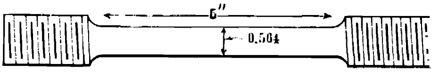
† See Howe's paper on simple overstrain in *Proc. A. S. T. M.*, Vol. 14, p. 8.

‡ *Proc. A. S. T. M.*, Vol. 17, p. 59.

TABLE 9.—COMPARISON OF TENSION AND COMPRESSION TESTS ON ANNEALED AND UNANNEALED STEEL BARS OF IDENTICAL MATERIAL WHICH HAD BEEN STRESSED BEYOND ITS ELASTIC LIMIT.*

Tension Tests.								Compression Tests.			
Marks.	How Taken.	Condition.	Elastic Limit per Square Inch.	Ultimate Strength per Square Inch.	Elongation in 5 In.	Contraction of Area.	E in 1,000,000 lb/in.²	Marks.	Elastic Limit per Square Inch.	Ultimate Strength per Square Inch.	E in 1,000,000 lb/in.²
			lb.	lb.	%	%			lb.	lb.	
1	Crosswise	Unannealed	40,000	66,320	12.0	24.6	30.2	3	51,000	58,100	34.3
2	"	Annealed	40,000	63,160	22.0	33.5	31.2	4	43,000	43,000	33.0
5	Diagonally	Unannealed	40,000	66,760	16.0	59.3	30.2	7	47,000	54,380	34.3
6	"	Annealed	42,000	62,840	27.5	61.5	30.7	8	40,000	43,000	31.8
9	Lengthwise	Unannealed	63,000	73,000	18.0	61.5	31.2	11	35,000	48,940	34.9
10	"	Annealed	47,000	64,000	26.0	61.5	30.7	12	42,000	45,000	32.4





Tension Specimen

* These specimens were cut from an eye bar which had been stressed to 54,350 lb. per square inch, 3 years and 3 mos. before these tests were made. The original elastic limit was 34,400 lb. per square inch. The position of the specimens in the original bar is shown in the figure above. The compression specimens were approximtely 0.92 in. in diameter. (From *Tests of Metals*, 1890, p. 731.)

The presence of impurities such as slag in wrought iron or carbon, in the form of pearlite, in steel appear to prevent grain growth. Consequently wrought iron and steel containing over 0.15 per cent carbon are not subject to grain growth.

Inasmuch as coarse grain makes the metal very brittle the phenomenon of grain growth bears an important relation to the properties of susceptible metals when worked in the cold and subsequently reheated. The phenomenon is often called "Stead's Brittleness," after J. E. Stead, who first investigated it.

Brittleness is also caused in low-carbon steel and wrought iron by prolonged working at a blue heat (225–300° C.). It appears quite likely that the crystal growth so produced originates from causes similar to those producing "Stead's Brittleness."

INFLUENCE OF FORM ON PROPERTIES

719. The effect of an abrupt contraction in cross-section of a bar under tension or bending is to cause high concentration of stress at the periphery of the groove or notch; also the shoulders of the groove or notch prevent free elongation of the metal at the contracted section and increase its strength. Fig. 40 shows the effects of various types of grooves on the distribution of stress in rectangular bars under tensile stress. The yield point of the iron used was 36,900 and the ultimate strength 56,500 lb. per square inch. The mean tensile stress in each case was 10,650 lb. per square inch. It will be noted that the calculated stresses at the root of the V-shaped notches exceeded the yield point of the metal.

The superior resistance per unit area of the steel at root of groove as compared with steel in uniform bars is shown by the tests of M. Duguet on hard steel and M. Barba on soft steel which are plotted in Fig. 41.

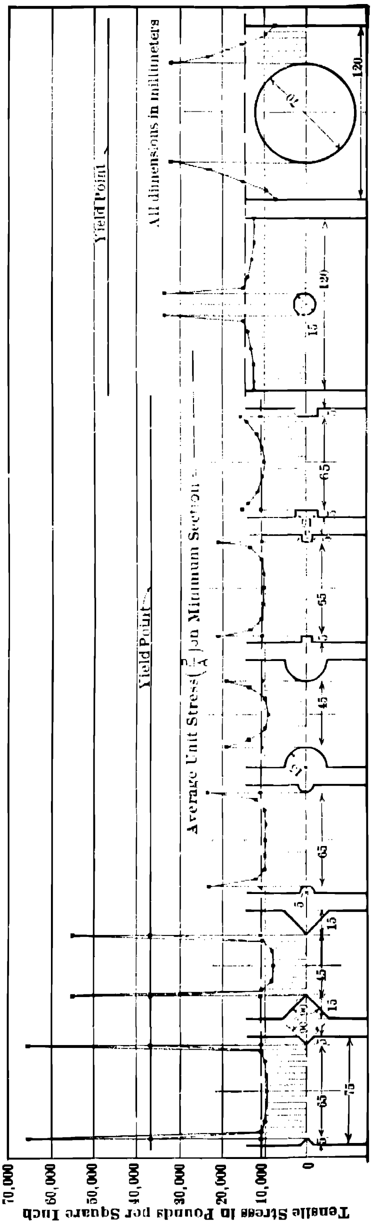


FIG. 40.—The Effect of Abrupt Changes in Rectangular Cross-sections on the Distribution of Tensile Stress. (E. Preuss, *Zeit. Vereines deutscher Ing.*, 1913, Pt. 1, p. 664; *Mitteil. über Forschungsarbeiten auf dem Geb. des Ingw.*, Vol. 126, p. 54.)

720. The Influence of the Form of the Thread on the Strength of Screw-bolts. — This subject has been investigated by Prof. Martens,* and his results are here given.

Two grades of mild steel were used for these bolts, all of which were cut from round bars originally 35 mm. (1.4 in.) in diameter. The softer material,

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* At the request of the German Society of Civil Engineers. The results were published in *Zeits. d. Ver. deutsch. Ing.* for April 27, 1896. The abstract here given was made by J. B. Johnson and published in the *Digest of Physical Tests* for July, 1896.

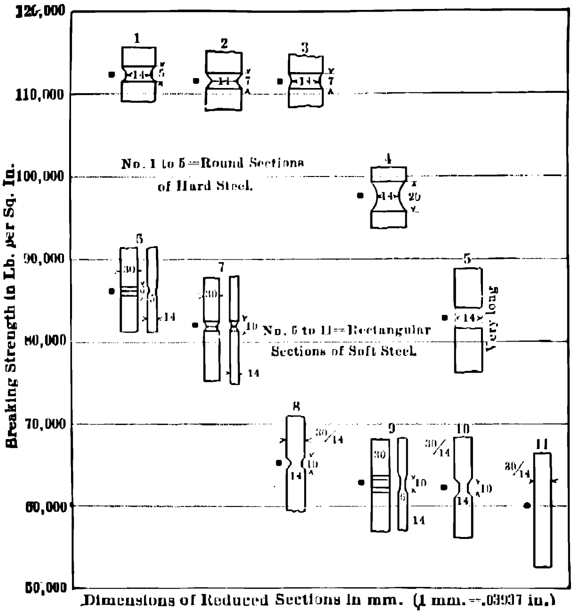
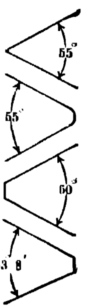


FIG. 41.—Effect of the Form of the Reduced Cross-section on the Tensile Strength of Two Kinds of Steel. (*French Com. Rep.*, Vol. 3, p. 40.)

having a tensile strength of 53,500 lb. per square inch, was used for screw-bolts approximately 1 in. in diameter, and the harder material, having a tensile strength of 62,000 lb. per square inch, was used for the screw-bolts, which were reduced to approximately ½ in. in diameter. Four such bolts were made of each of these sizes for each of the four styles of thread shown in Table 10, making in all 32 bolts with screw-threads which were tested. Two of each of these sets were tested in plain tension, the pulling force being applied to the inner face of the nut at one end, and increased until rupture occurred. The other two bolts of each set were tested also in tension, but

TABLE 10.—ABSOLUTE AND RELATIVE STRENGTHS OF THREADED BOLTS IN POUNDS PER SQUARE INCH. (MARTENS)

Kind of Thread.	Form of Base of Thread.	Diameter, In.	Stress Applied by			Proportion.				
			Machine.		Nut.	Test Bar = 100.			$S_g = 100$.	
			G.* S_g	T.* S_t	T. S_{tn}	S_g	S_t	S_{tn}	$\frac{S_t}{S_g}$	$\frac{S_{tn}}{S_t}$
(*a*) Sharp........		1	62,430	61,580	49,920	116.8	115.2	93.4	98.9	80.6
		½	71,100	70,400	62,720	114.9	114.0	101.4	99.2	88.2
(*b*) Whitworth....		1	62,160	61,300	44,800	116.2	114.6	83.8	98.9	72.2
		½	67,000	69,400	58,880	109.4	112.2	95.2	100.3	86.9
(*c*) Sellers........		1	60,300	60,020	52,330	112.8	112.2	97.9	99.6	86.9
		½	70,250	68,120	62,720	113.6	110.1	94.5	96.9	83.2
(*d*) German Soc. of Engr.......		1	60,730	61,160	47,640	113.6	114.4	89.1	100.7	78.6
		½	69,260	73,670	62,720	112.0	119.1	101.4	106.4	90.8
(*e*) Normal test bar.		1	....	53,480	....	...	...	100		
		½	....	61,860	....	...	...	100		

* G. = grooved; T. = threaded.

under a torsional action resulting from the continuous turning of the nut as the load increased to rupture. In this case the distortion resulting from the permanent elongation of the bolt was nearly all taken up by the movements of the testing-machine, the distortion taken up by the turning of the nut being the least possible to maintain a continuous torsional action at this point.

The same bars were also tested as plain tension-test specimens with cylindrical bodies, and again with grooves turned into them of the same shape as the corresponding screw-threads, leaving the same diameter at the bottom of the groove as obtained at the base of the threads. The actual and comparative average results of all of these tests are given in the table, from which the following conclusions may be drawn:

1. When subjected to plain tension both the screw-threads and the grooved sections were stronger than the plain bars of the same net area of cross-section, this excess of strength having an average value of about 14 per cent.

2. There is no very marked difference in the average strength of the bolts on which the several styles of thread were cut, the perfectly sharp groove shown at (*a*) in table being slightly stronger than the others.

3. The weakening effect of the turning of the nut under stress at rupture is much less than might have been predicted, when the distortion of the screw below the nut by permanent elongation is taken into consideration. The tests indicate for this case a strength of the 1-in. bolts about 10 per cent less than that of the plain bars, and of the ½-in. bolts about 2 per cent less than that of the plain bars.

4. In general it may be said that the turning of the nut upon the bolt at rupture reduces the strength of the net section of the bolt by about 20 per cent.

5. It is very probable that the four forms of screw-threads here shown would show very different results under fatigue tests from repeated stresses, and also for static loads on high-carbon steel. Under repeated loads and under shock it is probable that the sharp re-entrant angle of thread (*a*) would develop incipient cracks much earlier than either of the other forms, and that probably the Whitworth thread (*b*) would be the last to develop this kind of weakness, either with soft metal under repeated loads or with high-carbon steel under static loads.

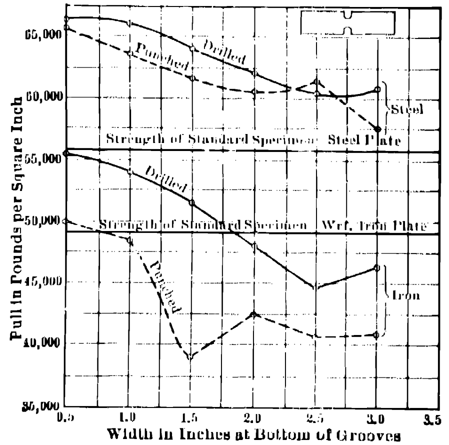


FIG. 42.—Variation in Strength of ¼-in. Plate for Varying Widths at Bottom of Groove. Each point represents 3 to 8 tests. (*Tests of Metals*, 1882.)

721. The Tensile Strength of Grooved Plates is a measure of the tensile strength of a riveted joint when failure occurs by tearing the plate. This strength is found to be a function of the width of the net section at the bottom of the groove, as well as of the method of making the hole, and of the character of the material. These effects are all shown in Fig. 42 for ¼-in. plates of wrought iron and of 56,000-lb.

steel. The steel, being more ductile, is stronger in the grooved than in the plain (standard) section, while the reverse is the case with wrought iron, except with drilled specimens, where the width of the net section was less than 1¾ in.

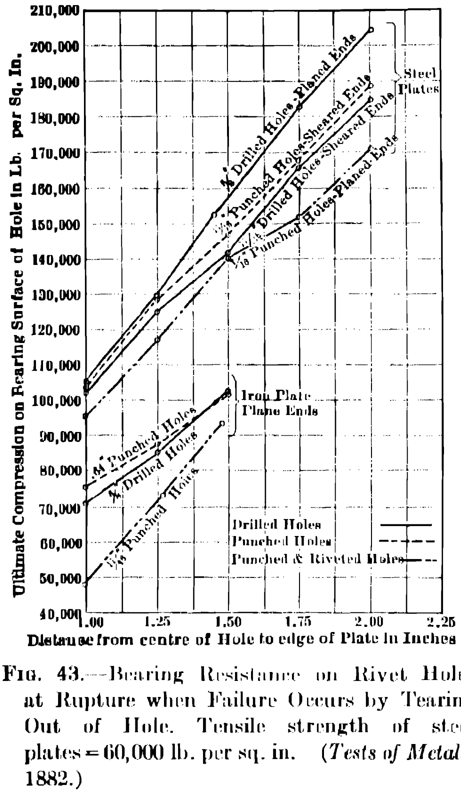


Fig. 43.—Bearing Resistance on Rivet Holes at Rupture when Failure Occurs by Tearing Out of Hole. Tensile strength of steel plates = 60,000 lb. per sq. in. (*Tests of Metals*, 1882.)

722. The bearing resistance of steel and iron plates ¼ in. thick (Fig. 43) is shown to increase directly with the distance of the hole from the edge of the plate when failure occurs by tearing behind the hole. With a factor of safety of 3 and a distance from edge to center of hole of 1⅛ in., the safe bearing unit stress would be 35,000 to 39,000 lb./in.^{2} for the steel and 20,000 to 26,000 lb./in.^{2} for the wrought-iron plates.

723. Resistance of Steel when the Compressed Area is Confined Laterally.—When a compressive load is applied over the full cross-section of a short prism or cylinder as in Fig. 44*a* the metal is free to flow laterally at all cross-sections excepting those in close proximity to the ends. If the load is uniformly applied over a portion of the surface as in Fig. 44*b*, the metal under the loading surface is laterally restrained by the ring of surrounding metal. The flow is therefore restricted and the elastic limit will be higher than for the first case. In Fig. 44*c* the elastic limit of the metal near the center of the impression is still higher, owing to greater strain and greater restraint.

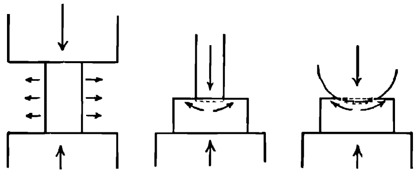

(*a*) Free Flow (*b*) Restricted Flow (*c*) Confined Flow

Fig. 44.

In Fig. 45 are shown a series of contact areas obtained by pressing sections of a cast-iron car wheel and of a locomotive steel driving wheel upon the top of a steel rail in a testing machine. The relation of the loads to the planimeter-determined contact areas is shown in Fig. 46. It will be observed that the plot is a straight line and the mean intensity of pressure for all loads was about 82,000 lb./in.^{2}

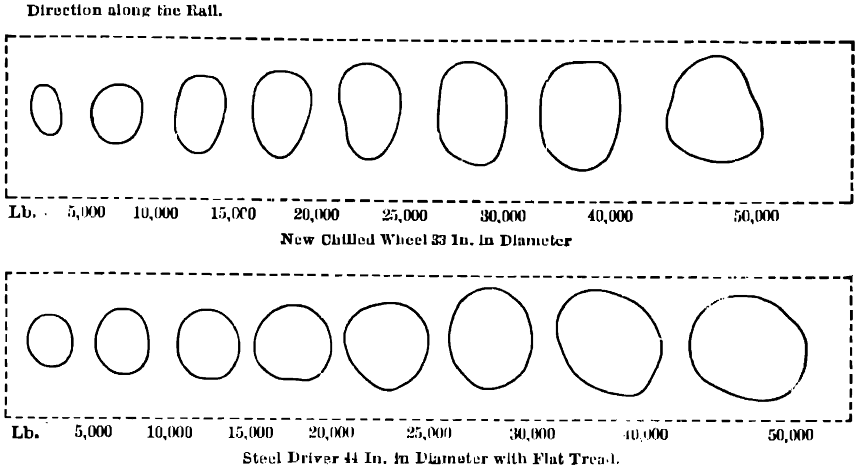

Direction along the Rail.
Lb. 5,000 10,000 15,000 20,000 25,000 30,000 40,000 50,000
New Chilled Wheel 33 In. in Diameter
Lb. 5,000 10,000 15,000 20,000 25,000 30,000 40,000 50,000
Steel Driver 44 In. in Diameter with Flat Tread.

FIG. 45.—Wheel Impressions on a 75-lb. Rail. Top Radius, 14 in. Areas are One-half Size.

Although the maximum stress at the center of these contact areas was probably 50 per cent more than the mean or 2½ times the elastic limit (50,000 lb./in.^{2}), yet no permanent set was observed.

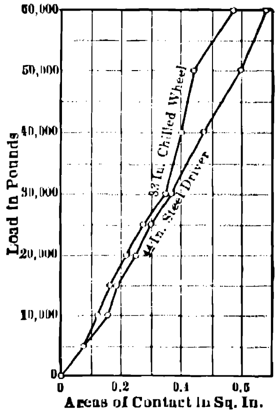


FIG. 46.—Showing Relation between Total Load and Area of Contact between Wheels and Rails. (Johnson, *Trans. A. S. C. E.*, Vol. 32.)

From tests on mild structural steel rollers 1 in. long resting on, or between, similar steel plates Crandall and Marston obtained the data plotted in Fig. 47. From these tests with small ratios of roller diameter (d) to length (l) the critical load in pounds per inch of roller was given by $p=880d$, where d is in inches. This relation is faulty since it does not include the effect of the ratio d/l for the roller.

After reviewing existing data, especially the tests of W. M. Wilson in *Bull.* 191 and 263, Engr. Expt. Sta., University of Illinois, V. P. Jensen suggested in *Bull.* 138, Iowa Engr. Expt. Sta., the following more general solution based on the strain energy theory of failure:

$$p=\left(1+\frac{1.78}{1+\dfrac{d^2}{800l^2}}\right)\frac{\pi S_y^2 d}{E}$$

Here S_y is the yield point of the metal. This equation agrees fairly well with Wilson's results, which cover a wide range in d/l. Wilson's tests also indicated that the thickness, t, of the bearing plate in inches should not be less than $t = 1.0 + 0.004d$.

Load-bearing tests on knife-edges for scales were also reported by Wilson in *Bulletin* No. 242, Engr. Expt. Sta., Univ. of Illinois. In these knife-edge tests the criteria for determining the critical load was an increase of 0.005 in. in the width of the knife-edge. It was found that the critical load varied directly with the width of the knife-edge for a range in width of 0.004 to 0.04 in. The critical load for knife-edges also varied with the angle at the edge. For knife-edges with an angle of 120 deg., the critical load was about 50 per cent greater than for those with 30-deg. angles. For 90-deg. knife-edges having a Rockwell hardness number between C50 and C60 the average unit-bearing pressure was 400,000 lb./in.,^{2} or 4,000 lb./in. for a knife-edge 0.01 in. wide. Successive applications of loads less than the critical failed to cause any plastic flow.

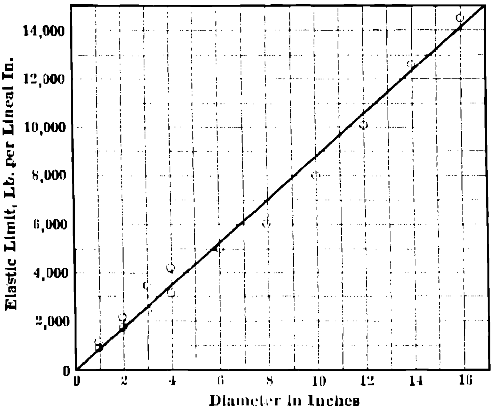


FIG. 47.—The Elastic Limit per Lineal Inch of Rollers of Various Diameters. (Crandall and Marston, in *Trans. Am. Soc. Civ. Engr.*, Vol. 32, p. 120.)

For elastic stress formulæ for cylindrical and spherical bodies in contact, see article by R. J. Roark in *Product Engr.*, Vol. 9, No. 7, p. 278.

724. Properties of Wire.—We have already considered the effects of drawing, patenting and annealing on the properties of wire in Art. 716. To determine the quality of wire it has been customary to subject specimens to tensile, cold bending and torsion tests. If the tension test is so made that a complete stress-deformation diagram is obtained, it appears to furnish the essential information. From such a test the strength, elastic limit, and ductility can be read directly, and the toughness can be roughly estimated from the area of the diagram. The per cent elongation is not only an index of ductility but is also a valuable criterion of the wearing quality of the wire when made into rope. The cold-bend test is usually made by clamping one end of the wire between jaws having a radius of $\frac{1}{8}$ in., or equal to the diameter of the wire, and bending the projecting portion back and forth through an angle of 180° until failure occurs. The number of bends required for rupture constitutes a measure of ductility and capacity to receive cold work. The wrapping test, a measure of ductility, is commonly made on wires from wire rope. Main wires should withstand without failure wrapping 6 complete turns in a close helix on a mandrel with diameter twice that of the wire. Torsion tests are made on a gage length of 8 in. The number of turns withstood under a constant tension constitutes a measure of ductility and uniformity.

The strength and ductility of wire depend upon the drawing and heat treatment and also upon the diameter of the finished wire. Annealed iron wire has a tensile strength of 50,000 to 60,000 lb. per square inch. The same material hard drawn with a diameter of an eighth of an inch will have a strength of 70,000 to 80,000 lb. per square inch, when drawn to a very fine wire it may have a strength of 100,000 lb. per square inch. The strength of steel wire is of even greater range, depending upon composition in addition to the previously mentioned factors. Thus we find low-carbon hard-drawn wire with an ultimate strength of 90,000 to 100,000 lb. per square inch and high-carbon hard-drawn piano wire with a strength of 300,000 to 400,000 lb. per square inch. A strength of 447,000 lb. per square inch is recorded for a piano wire 0.63 in. in diameter containing 0.80 per cent carbon.*

The following requirements are largely from government specifications.

MINIMUM REQUIREMENTS OF WIRE FOR ROPE

Kind of Wire	Tensile Strength, lb., in.^{2}	$\frac{\text{Twists}}{\text{Diameter}}$
Iron	70,000	3.2
Traction steel	160,000	2.6
Cast steel	170,000	2.6
Extra strong cast steel	190,000	2.4
Plow steel	210,000	2.2
High grade plow steel	230,000	2.0
Bridge cable †	220,000	4% elong. in 10 in.

The proportional limit of the last 6 types of wire is from 65 to 75 per cent of the tensile strength.

725. Wire rope is made by twisting 7 to 42 wires, 0.02 to 0.05 in. in diameter, into strands then twisting 3 to 6 such strands into a rope. The rope diameter is that of the circumscribing circle. Ropes are made from $\frac{1}{4}$ to $2\frac{3}{4}$ in. in diameter and bridge cable up to 36 in. in diameter. Common wire rope is twisted from six strands, each of which consists of 7 to 19 individual wires. In ordinary rope the strands are twisted in the opposite direction to the twist of the wire in the strands; but in rope which must have high resistance to abrasion both wires and strands are twisted in the same direction, thus forming the Lang-lay rope. Where great flexibility is desired the rope is provided with a hemp core, or, if the wear is not great, a larger number of wires may be used in the strands. For elevators and other hoisting purposes where the loads are light, the speeds high and the wear on sheaves is considerable, an iron wire rope gives good service. For derricks, mine hoists, cableways, conveyors and uses where considerable strength and abrasive resistance is required, cast-steel wire rope has the requisite strength and durability. Plow-steel wire rope is used in deep mine hoists, on dredges, stump pullers, and under conditions where maximum strength and toughness are wanted. For the fixed lines in aerial cableways where very great wearing resistance is wanted, a rope with a smoother surface is sometimes used. One of the two common types is the steel-clad wire rope in which each strand is spirally wound with flat steel strips. The other is the locked-wire rope in which the surface layer is made of wires drawn to such a shape that they interlock when twisted about the rope and form a true cylindrical surface. Flat ropes are also used for hoisting purposes.

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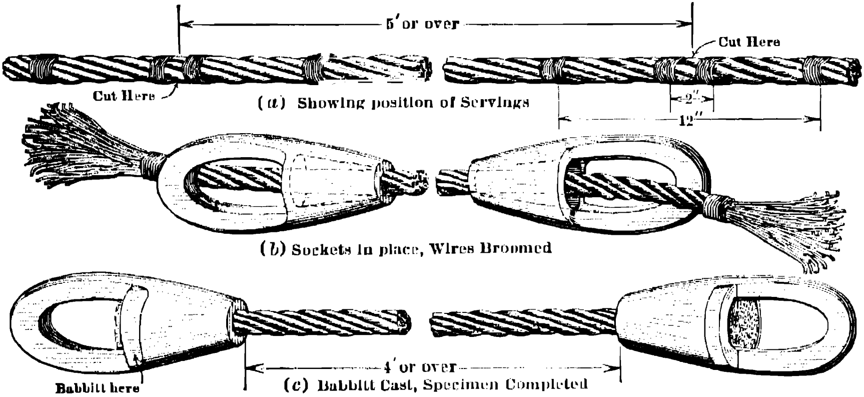
* *Tests of Metals*, 1894, p. 347.

† Cold drawn preferred to heat treated.



(a) Showing position of Servings

(b) Sockets in place, Wires Broomed

(c) Babbitt Cast, Specimen Completed

FIG. 48.—Method of Socketing Wire Rope.

The strength of wire rope is difficult to obtain from short specimens because of the small stretch of the wires and the non-uniformity in stretch due to variation in the rigidity with which they are held. A fairly satisfactory method of gripping the ends follows. A length of 5 ft. or more should be marked off on the rope and two sets of four servings (or windings) with black iron wire should be made at each end of the marked length as shown in Fig. 48*a*. The rope should be cut at the marks by means of a cold chisel and the servings will prevent unraveling. Conical sockets may now be slipped over the ends of the rope, the outer servings removed and the wires broomed as shown in Fig. 48*b*. If there is a hemp core it should be cut back to the inner servings. The wires are cleansed by dipping in gasoline followed by hot caustic potash. After cleaning, the wires should be dipped in zinc chloride and thoroughly tinned in the molten babbitt used to fill the socket. The sockets can then be pulled over the cable ends and the babbitt poured into the socket in such manner as to completely fill it. Alloys used with success at the University of Wisconsin are: Lead, 83 per cent; tin, 7 per cent; antimony 10 per cent, also lead, 60 per cent; tin, 30 per cent; antimony, 9 per cent, and bismuth, 1 per cent.* Both of these melt below 550° F. Government specifications require the use of zinc cast at a temperature below 830° F. After socketing, the specimen is ready for the testing machine.

In Table 11 is given a summary of several hundred tests on high-grade wire and on ropes made of it. These tests were conducted with great care by Tetmajer. The tension and torsion results on wires were determined from autographic diagrams, consequently the ductility measurements include the elastic deformations. For a wire having a strength

TABLE 11.—RÉSUMÉ OF TESTS ON CRUCIBLE CAST-STEEL WIRE AND WIRE ROPE USED ON CABLE RAILWAYS IN SWITZERLAND.

(From *Tetmajer's Communications*, Vol. 4, p. 272.)

Number of Cable.	Test of Entire Cable. (Each the Mean of Two Tests.)			Test of Individual Wires. (Each the Mean of Eleven Tests.)					Ratio of Strength of Cable to Average Strength of Wires.
				Tension Test.			Torsion	Bending.	
	Diameter in Inches.	Tensile Strength in Pounds per Square Inch of Actual Wire Section.	Per Cent of Elongation in 8 ft.	Strength in Pounds per Square Inch.	Per cent of Elongation in 20 Inches at Rupture.	Work of Deformation in Foot-pounds per Cubic Inch.	Number of Twists of (360°) in 8 Inches.	Number of Bends of 180° Each on ¼-in. Radius.	
1	1.65	220,000	3.12	265,000	3.4	6,400	27.5	11.4	83
2	1.67	117,000	7.45	122,000	9.4	9,500	61.5	11.8	96
3	1.18	205,000	2.61	213,000	3.0	4,600	35.1	17.8	96
4	1.43	191,000	3.30	207,000	3.4	5,000	44.5	18.0	93
5	1.00	184,000	3.92	191,000	3.85	5,300	.....	15.1	96
6	1.00	184,000	3.28	190,000	4.0	5,700	52.6	14.8	97
7	1.38	180,000	2.37	222,000	3.0	4,600	33.7	11.0	77
8	1.30	226,000	3.00	247,000	3.3	5,700	21.7	9.6	92
9	1.26	210,000	3.15	238,000	3.3	5,400	31.1	9.4	89
10	1.00	190,000	2.40	190,000	2.7	3,400	48.1	18.8	100
Average (omitting No. 2).		199,000	2.98	217,000	3.29	5,100	36.8	14.0	92

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* Tetmajer used an alloy of 8 parts tin, 1 part antimony and 1 part copper for iron and mild steel wires; for hard steel wires he used 9 parts lead, 2 parts antimony and 1 part bismuth.

of 200,000 lb. per square inch the elastic stretch amounts to 0.7 per cent. Consequently the per cent elongation as measured across the break after rupture was about 0.7 or 0.8 per cent less than the values recorded in the sixth column of the table.

In long wire ropes on a straight pull the strength of the rope may be taken as about equal to the average strength of the individual wires if these are all of about the same ductility and ultimate strength. If the wires differ greatly in ductility, the ultimate strength of the rope is the average resistance of the wires at that percentage of elongation which corresponds to the total elongation of the least ductile samples. It is common to assume the rope to have 85 per cent of the total strength of the wires when tested individually. The total area (a) of the wires in a rope may be calculated from the following: Ordinary rope with hemp core, $a=.46d^2$; ordinary rope with steel core, $a=.50d^2$; locked wire rope, $a=.74d^2$; where $d=$diameter of rope. The weights in pounds per lineal foot (w) of the same ropes may be estimated by the following equations: $w=1.58d^2$, $w=1.70d^2$, and $w=2.5d^2$, respectively. A factor of safety of 5 is commonly used in figuring working loads, but for passenger elevators and conditions where failure in the rope may endanger life, the factor should be increased to 8. The modulus of elasticity of wire rope after several loadings usually is between 14,000,000 and 16,000,000 lb./in.^{2} of metal in cross-section. Values for initial loading are about half the above.

Wire-rope pulleys, sheaves, and barrels should have a diameter not less than one hundred times the diameter of the ropes running upon them, to prevent excessive bending strains in the ropes.

STEEL UNDER COMBINED STRESS

726. Effects of Combined Stress upon the Elastic Limit.—A statement concerning the theories underlying the causes of elastic breakdown has been made in Art. 41. We shall now briefly consider some experimental evidence showing the weakening effects produced by a combination of torsion and direct or bending stresses.

The influence of combined stress in lowering the elastic limit is shown in Fig. 49. These results were obtained by Hancock at Purdue University * from experiments on steel tubing and steel shafting. The deformations both in tension and in torsion were measured with apparatus of sufficient accuracy to permit the determination of the elastic limit (really the limit of proportionality). It seems rather doubtful if the measurements of deflection were sufficiently accurate to detect the overstrain in the extreme fibers of the specimens under flexure.

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* Reported in *Proc. A. S. T. M.*, Vol. 7, p. 267.

Curves 1, 2 and 3, represent the effect of an initial torsional moment in lowering the elastic limit in flexure, compression and tension, respectively. Thus, if an initial twisting moment sufficient to stress the outside fiber of a round bar to one-half of its elastic limit in shear is applied and the bar is then axially compressed under progressively increasing loads, curve 2 shows that the elastic limit in compression will be found at 79 per cent of the load which the bar could carry under simple compression. It appears that curve 1 is too high, probably due to the difficulty of determining by deflection increments when the outside fiber had been overstrained. Curve 4 shows the influence of an initial tensile or compressive stress on a round bar subjected to torsion.

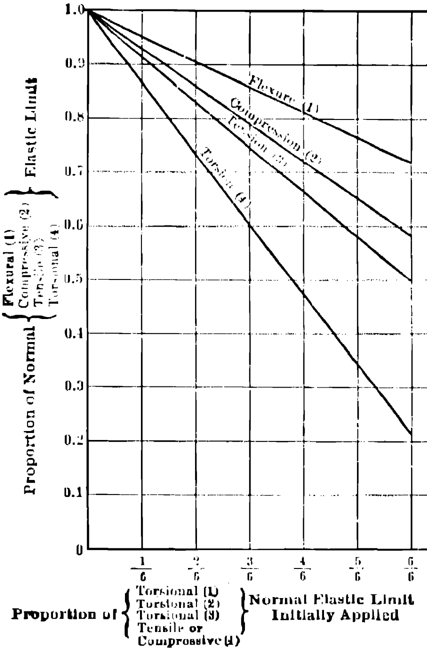

FIG. 49.

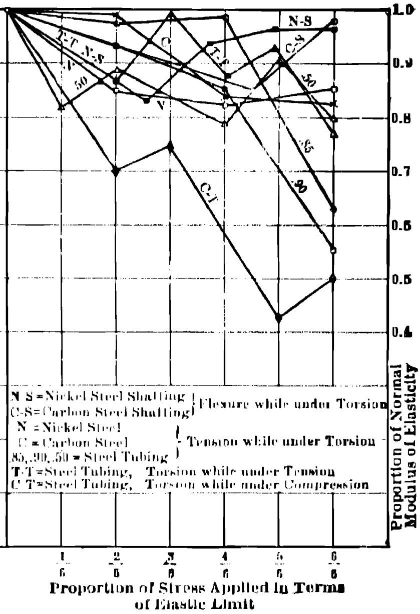

FIG. 50.

FIG. 49.—The Influence of Combined Stress on the Elastic Limit. (Hancock.)
FIG. 50.—The Influence of Combined Stress on the Modulus of Elasticity. (Hancock.)

727. Effect of Combined Stress on the Modulus of Elasticity.—Hancock's tests also show that the modulus of elasticity in tension and in torsion is considerably decreased by combined stress, whereas the effect of combined stress on the modulus of elasticity in flexure is less, Fig. 50. The results are, however, much more irregular than those from which Fig. 49 was derived.

CHAPTER XXIV

ALLOY STEELS

728. Varieties of Alloy Steels and Their Manufacture.—Those steels which owe their peculiar properties to the presence of one or more elements besides carbon, or to the joint action of such elements and carbon, are termed alloy steels. In a general way we may say that these alloying elements influence the properties of steels through the changes which they affect, (1) in constitution and structure, (2) in shifting the position of the critical ranges on heating and cooling, and (3) in promoting stability of structure under wide temperature variations. When the distinctive properties are produced by the addition of one element to a carbon steel, a *ternary alloy*, consisting of iron, carbon and the element, is formed. When two such elements are added to a carbon steel a *quaternary alloy* results. The more important alloy steels are the ternary alloys made with nickel, manganese, chrome, tungsten, vanadium, silicon—the quaternary alloys, chrome-nickel, chrome-molybdenum, and chrome-vanadium steels, and the high-speed steels which are more complex alloys.

The alloy steels which are turned out in large tonnages like the nickel, silicon, chrome-nickel, chrome-vanadium and manganese steels are generally manufactured in the acid open-hearth furnace. Nickel may be added with the charge, but the other elements are added just before pouring, or in the ladle, to prevent losses through oxidation. Tungsten steels and high-speed steels are generally made in the crucible or electric furnace.

729. Nickel steel is, from the standpoint of tonnage and variety of uses, the most important of the ternary alloys. Although additions of nickel to pure iron[†] effect large increases in strength and hardness with accompanying losses in ductility, the commercial alloys generally contain carbon with small percentages of the other impurities common to carbon steels. Nickel apparently forms a solid solution with iron, reduces the solubility of carbon in iron, and produces marked changes in the position

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[*] References: *Steel and Its Heat Treatment*, by D. K. Bullens; "Topical Discussion on the Role of the Several Alloying Elements in Alloy Steels," *Proc. A. S. T. M.*, Vol. 17, p. 5-57; *Bull.* No. 100 *U. S. Bureau of Mines; Manufacture and Uses of Alloy Steel*, by H. D. Hibbard; *Monographs on Alloys of Iron Research*, Battelle Memorial Institute.

[†] *Bull.* No. 346, Univ. of Wisconsin, by Burgess and Aston.

of the critical range. On account of these influences the constitution, the mechanical and the electrical properties of nickel steel are greatly altered by variations in the nickel content.

The relation of nickel and carbon content to the constitution of nickel steel as cast is shown in Fig. 1*a*. Fig. 1*b* shows the influence of nickel on the magnetic point (*Ar_2* or *Ac_2*) of nickel-iron alloys. It will be noted that alloys containing less than 25 per cent nickel are irreversible (transformations in heating take place at much higher temperatures than in cooling), but alloys containing over 25 per cent of nickel are reversible. Although evidence is incomplete, the critical ranges of nickel steels are effected in somewhat the same manner as the above. Since nickel lowers the solubility of carbon in iron, it is not possible to carry over .50 to .60 per cent carbon in nickel steels which are to be annealed on account of the tendency of carbon to separate on slow cooling from above the critical range and form graphite.

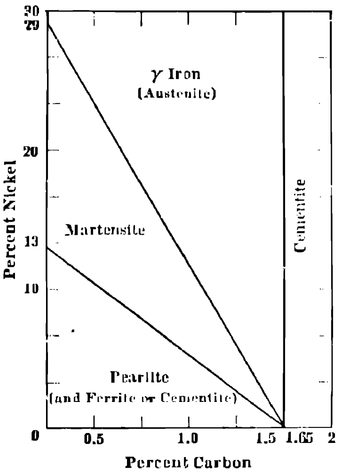

Fig. 1 *a*.

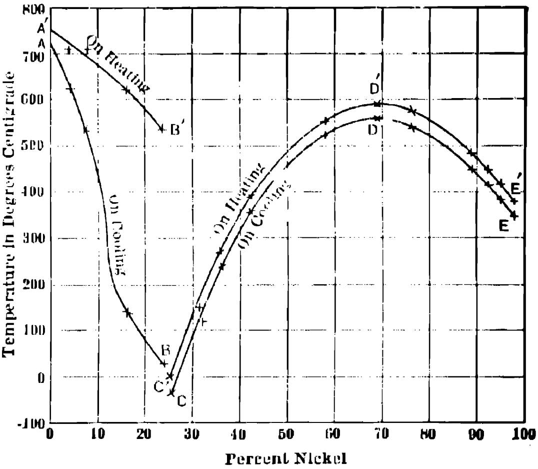

Fig. 1 *b*.

Fig. 1*a*.—The Constitution of Nickel Steels. (Guillet, *Jour. Ir. and St. Inst.*, Vol. 70, p. 4.)

Fig. 1*b*.—Effect of Nickel on Critical Points. (Osmond, *Comptes Rendus*, Vol. 128, p. 306.)

From a consideration of the constitution diagram (Fig. 1*a*) we should expect the low-nickel (pearlitic) steels to possess high strength and good ductility, those of medium-nickel content (martensitic) we should expect to be much stronger and far more brittle while those of high-nickel content (austenitic) should be strong and ductile. These expectations are roughly borne out by the experimental results of Giesen which are plotted in Fig. 2. In toughness the austenitic nickel steels of a given carbon content are superior to the pearlitic, which in turn greatly surpass the martensitic steels. Because of these mechanical properties, the low and high-nickel steels are of most use.

Low-nickel Steels.—On account of the high cost of nickel only the low-nickel steels have entered the structural field. Most of the structural nickel steels contain 3 to 4.5 per cent of nickel and 0.15 to 0.40 per cent carbon. Advocates of structural nickel steel claim that it has greater toughness and ductility than a carbon steel of equal strength. It is also claimed that it is freer from segregation but is more liable to blow-holes and fissures than carbon steel It possesses excellent machining qualities but cannot be welded. Low-nickel steels are somewhat superior to carbon steels in resisting corrosion; high-nickel steels are very markedly superior.

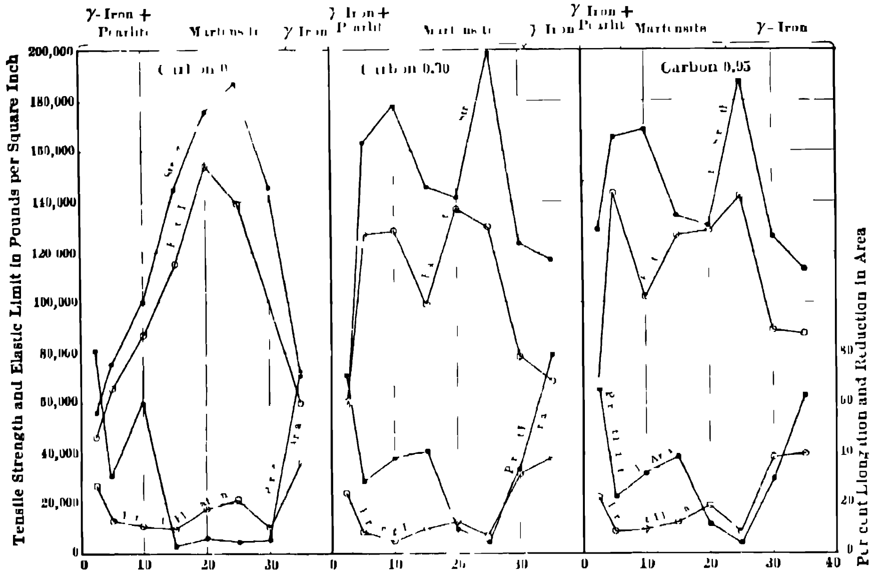

FIG 2 —The Influence of Nickel on the Strength and Ductility of Steel (Giesen, *Carnegie Fellowship Memoirs*, Vol 1, p 1)

Abbott * states that each per cent of nickel added to the low-nickel steels (Ni < 8 per cent) lowers Ac_1 about 10.3 C°. The other critical points are also depressed nearly as much On cooling, the lowering effect on the critical points of these steels is nearly twice as great as in heating.

When heat-treating nickel steels it is necessary to hold them longer than carbon steels at temperatures above the upper critical point in order that transformations may be completed Since nickel steels are less liable to injury through overheating than carbon steels, double quenching affords an excellent although somewhat costly method of equalizing the structure in hardened steel. Double quenching consists in heating the steel to a temperature considerably in excess of the upper critical point, quenching, reheating to a temperature just above the upper *Ac* point to refine the grain and again quenching. Otherwise the heat treatment of low-nickel steels is carried on in manner similar to treatment of carbon steels.

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* *Proc A. S. T M*, Vol 17, p 13

Abbott also states that the strength of a given carbon steel is increased by 4200 lb. per sq. in. for each per cent of nickel added up to 8 per cent and the elongation is reduced by 1 per cent. Thus a 0.30 per cent carbon steel having an ultimate tensile strength of 70,000 lb. per sq. in. would have its strength increased to 85,000 lb. per sq. in. by the addition of 3.5 per cent of nickel and its elongation reduced 3.5 per cent. With ¾-in. bars he states that the tensile strength of hardened and drawn nickel steel is increased by (29400–21.4 T) lb. per sq. in. for each per cent increase in nickel, T indicating the drawing temperature in degrees C. The elastic limit is likewise raised by (28700–17.4 T) lb. per sq. in. for each per cent of nickel added. Hardening lowers the per cent elongation about 0.73 per cent for each per cent of nickel and drawing does not affect this reduction appreciably. Comparing with carbon steels, we note that structural nickel steels have greater resistance to impact than carbon steels * for like uses. Heat treatment seems to make the superiority of the nickel steels more marked.

These steels are used considerably in long-span bridge construction, for shafting, rifle barrels, ordnance, axles, bearings, forgings, and castings.

High-nickel steels containing from 30 to 35 per cent of nickel and less than 0.40 per cent carbon possess great resistance to shock, a tensile strength of 85,000 to 95,000 lb. per sq. in., an elastic limit of half that amount, and an elongation of 35 to 40 per cent in 2 in. The modulus of elasticity of these steels is low, being about 23,000,000 lb. per sq. in. Since these high-nickel steels have very good resistance to corrosion they are well adapted to valves and spindles for gas engines, boiler tubes, and for wire netting and cables which are to be used in salt water.

Steels with 25 per cent of nickel are practically impermeable to magnetism unless cooled below −50 °C. when they become magnetic and remain so after returning to atmospheric temperatures (see Fig. 1*b*.) Steels of 30 to 35 per cent nickel are magnetic at ordinary temperatures but have much lower permeability than carbon steels. They do not suffer material change in permeability due to heat treatment.

Invar, an alloy of iron with 36 per cent nickel and 0.50 per cent carbon, has a coefficient of expansion of only 0.000001 per °C. It is most useful in making steel measuring tapes and bars, clock pendulums and other apparatus in which dimensional changes due to temperature must be made as small as possible. *Platinite*, a nickel steel containing about 46 per cent nickel and a low percentage of carbon, finds useful application because it has the same coefficient of thermal expansion as glass.

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* See Tests by W. K. Hatt in *Trans. Am. Soc. C. E.*, Vol. 63, p. 307.

730. Manganese steel is the term applied commercially to alloys of iron containing from 10 to 14 per cent of manganese and 1 to 1.3 per cent of carbon. Inasmuch as manganese exerts twice as powerful an influence as nickel in lowering the critical temperatures of the iron-carbon alloys and also renders the rate of transformation at the critical points very sluggish, it exercises a most potent effect on the constitution and properties of the metal. Fig. 3 shows the variations in structures of the alloys due to changes in manganese and carbon content. It will be noted that the commercial manganese steels are austenitic and experiments have shown that they have no well-defined critical points. In cast or rolled form, the steel is glassy brittle owing to the separation of manganese-iron carbide which, in slow cooling, forms a weakening network around the austenite grains. By reheating the steel to a temperature between 1000 and 1100° C. and quenching in water, separation of the carbide is prevented and a fine-grained uniform austenitic structure is secured. As a consequence of this heat treatment the ductility and toughness is wonderfully improved.

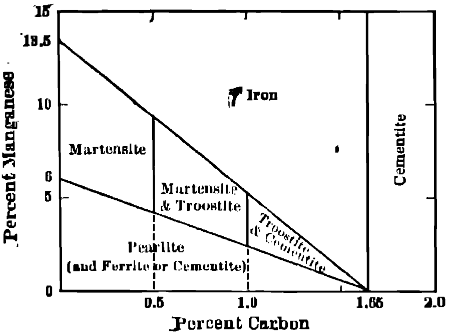

FIG. 3.—The Constitution of Manganese Steels (Guillet, *Jour. Ir. and St. Inst.*, Vol. 70, p. 7.)

Fig. 4 shows the tensile properties of various manganese steels as determined by Hadfield, who first investigated their properties. It will be observed that the ultimate strength of the water-toughened specimens of the commercial alloys is about 140,000 lb. per sq. in. and the elongation between 40 and 50 per cent. The elastic limit is, however, quite low, being only 50,000 lb. per sq. in. The steel exhibits no necking in the tensile test and consequently has a low per cent reduction in area. In shock resistance, it is far superior to carbon steels of equal strength. The Brinell hardness number of the commercial steel is only 200, or thereabouts, but it possesses extremely high resistance to certain types of abrasion. Howe * attributes this resistance to its capacity of hardening under deformation. The austenitic manganese steels are non-magnetic and possess high electrical resistance.

On account of the impossibility of softening by heat treatment, manganese steel cannot be machined. Therefore it can only be used advantageously in shapes which can be cast or rolled to approximately final form and finished by a comparatively small amount of grinding.

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* *Proc. A. S. T. M.*, Vol. 17, p. 7.

Water-toughened manganese steel is effectively utilized for rails on curves where wear is severe, for frogs and switches, for vaults and safes, for screens in separating stone, for crusher jaws and rolls.

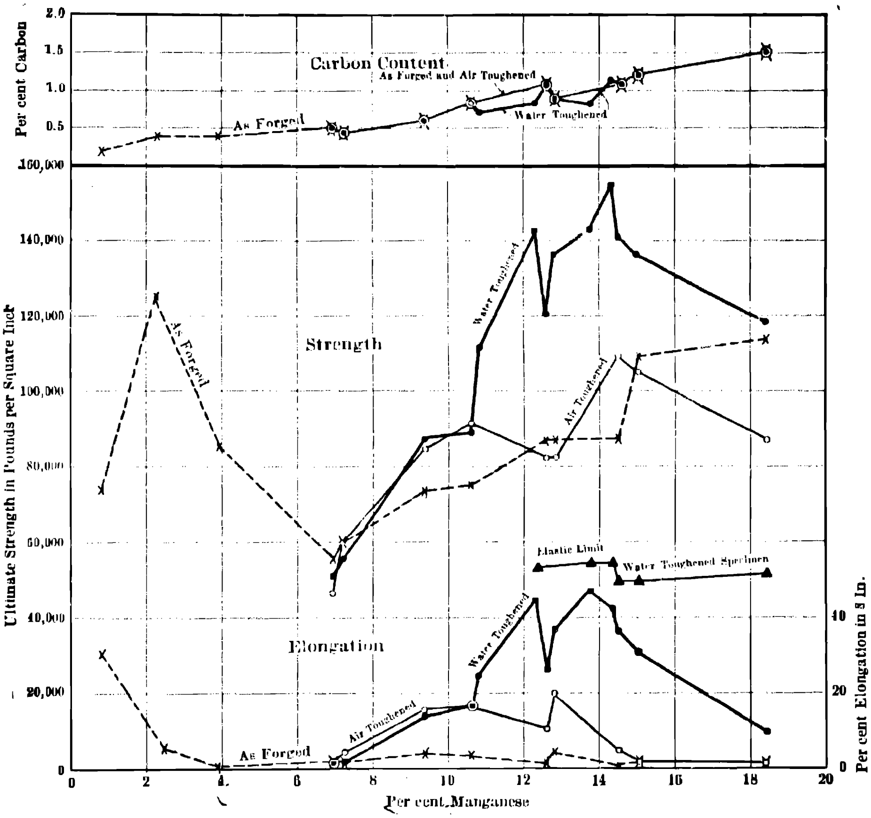

FIG. 4.—The Influence of Manganese on the Strength and Ductility of Steel. Specimens were ¾ in. in diameter. (Hadfield, *Proc. Inst. Civ. Engr.*, Vol. 93, p. 1.)

The martensitic manganese steels are of little commercial value on account of their excessive brittleness.

731. Chrome steels containing 0.5 to 2 per cent chromium and 0.2 to 1.5 per cent carbon find considerable application for parts where great hardness, high strength and a fair degree of toughness are required. The great hardening capacity of the chrome steels is due to the combination of chromium with cementite, thus forming a double carbide with iron. Chromium also promotes a very fine-grained structure in the metal.

Steels of the composition mentioned above are pearlitic in the normal state. In the annealed state they have somewhat greater ductility than carbon steels of equal strength, but subsequent to proper quenching and tempering, they are much stronger and harder, and somewhat tougher and more ductile than carbon steels. Chrome steels also have a very high elastic ratio. In toughness, however, they are excelled by the chrome-nickel and chrome-vanadium steels.

Since austenite does not readily dissolve the double carbide it is necessary in annealing chrome steels to soak them for several days at a temperature just above the critical range, which is 25 to 50° C. higher than for carbon steels of like carbon content, and then cool very slowly. Excepting the differences in critical points, chrome steels are hardened and drawn in much the same way as carbon steels. Table 1 shows the influence of hardening and tempering on chrome steels.

TABLE 1.—MECHANICAL PROPERTIES OF CHROME STEELS

Chemical Analysis.	Treatment.		Strength in Pounds per Square Inch.		Per cent Elongation in 2 Inches.	Brinell Hardness.	Authority.
	Quenched at, ° C.	Drawn at, ° C.	Ultimate.	Elastic Limit.			
C = 0.64							
Cr = 1.01	870	400	227,500	170,000	5.0	477	
Mn = 0.28	870	500	212,000	155,000	8.0	444	* Bullens
Si = 0.17	870	600	186,000	127,500	10.0	387	
	As forged		78,800	51,100	30.5	AC_3	
C = 0.20	800	400	153,600	150,100	12.5		
Cr = 1.98	800	550	130,000	123,200	16.0	822° C.	
Mn = 0.12	800	700	92,300	71,600	28.0		† McWilliam
	Annealed		73,900	35,800	40.5		
	As forged		120,500	71,700	20.5		
C = 0.50	800	400	255,700	251,000	9.0		
Cr = 1.09	800	550	201,000	190,500	13.0	778° C.	and
Mn = 0.24	800	700	139,800	127,700	21.0		
	Annealed		84,200	28,700	28.0		
	As forged		170,000	116,500	10.0		
C = 0.85	800	400	......	......	......	......	Barnes
Cr = 2.00	800	550	214,200	207,000	8.5		
Mn = 0.24	800	700	141,100	128,800	20.0	777° C.	
	Annealed		89,800	42,100	32.0		

* Specimens used by Bullens (see *Steel and Its Heat Treatment*, p. 302) were 1 inch rounds quenched in oil.

† Specimens of McWilliam and Barnes (see *Jour. Iron and Steel Inst.*, Vol. 81, p. 253) were quenched in water. They were 0.564 inch in diameter.

Heat treated *Stainless Steel* containing about 0.3 per cent carbon and 13 per cent chromium well resists corrosion and is much used for cutlery.

Steels with about 0.5 per cent of chromium and 0.60 to 0.90 per cent carbon are used for chipping chisels, drills, razors and saw-blades. Files are made from 0.5 per cent chrome steel containing about 1.5 per cent carbon. Steels containing about 1.0 to 1.5 per cent chromium and 0.90 to 1.10 per cent carbon are used in balls and rollers for bearings, also for safes and crusher jaws. Projectiles, rolls for cold-rolling metals, and drawing dies are made from steels containing about 2 per cent chromium.

Stellite, an alloy of cobalt, chromium and tungsten, though not a steel, competes successfully with steel for tool edges, and has been used to advantage to surface portions of crushing machinery, plow shares, valves, and other parts subjected to severe wear. Stellite requires no heat treatment and tools made of it can be run successfully at a red heat. Where it is desirable to form a thin hard edge or surface, stellite can be welded to iron or steel with an oxy-acetylene torch. The metal has approximately the same electrical and thermal conductivity as copper. It is highly resistant to corrosion and will take a high polish. The latter properties make it useful for reflecting surfaces.

732. Tungsten steel is the oldest of the alloy steels but is of minor importance at the present time. The chief use now made of this ternary alloy is in permanent magnets, for which purpose the steel is unexcelled. Magnet steels usually contain about 0.6 per cent of carbon and 6 per cent of tungsten. After the magnets have been formed they are hardened and then soaked for a long time at the temperature of boiling water in order to stabilize their magnetic properties. Steels with about 3 per cent of tungsten and 1 per cent of carbon are used to some extent for lathe tools for rapidly finishing iron and steel parts. Such steels are heat treated much like carbon steels.

Tungsten steels are very complex in constitution. According to results which Arnold and Read * obtained by experimenting on steels containing 0.7 per cent carbon, if in annealed steels the ratio of carbon to tungsten is 1 : 15.3 these elements are united as a carbide (WC); if the carbon is in excess of this ratio both carbides of iron and tungsten are present; if tungsten is in excess there is no carbide of iron, but a mixture of carbide of tungsten and tungstide of iron (Fe_2W) is present. When the tungsten steels are heated to temperatures above 1000° C. the lower critical point is depressed very markedly. This effect of tungsten on the critical point A_1 has a very important bearing on the properties of the high-speed steels of which tungsten is a part.

Swinden's researches † show that the strength of 3 per cent tungsten steels increases from 74,000 to 139,000 lb. per sq. in. as the carbon content is raised from 0.2 to 0.9 per cent, the per cent elongation in 2 in. falling from 28 to 13.5 per cent for the same change in composition. Further increase in carbon produced a decrease in strength. With steels containing 0.8 per cent carbon and tungsten ranging up to 19 per cent Portevin ‡ obtained a maximum strength of 192,000 lb. per sq. in. with a tungsten content of 10 per cent. The steel was, however, quite brittle.

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* *Proc. Inst. Mech. Engr.*, 1914, Pt. 2, p. 223.

† *Jour. Iron and Steel Inst.*, 1907, Pt. 1, p. 294.

‡ *Carnegie Fellowship Mem.*, Vol. 1, p. 261.

Both the strength and hardness of tungsten steels can be raised materially by heat treatment.

733. Vanadium Steel.—Although the strength and hardness of steel is improved by additions of vanadium up to 1 per cent, the element is so expensive that the content usually is kept much lower, running from 0.10 to 0.20 per cent in commercial vanadium steels. Vanadium is one of the most powerful of the alloying elements in raising strength and hardness. Vanadium is also a powerful scavenger of oxygen but is too costly to use for such purposes.

In low percentages, vanadium combines with both the ferrite and pearlite of the steel. In the latter it enters the cementite as a double carbide with iron and thus exerts a pronounced hardening influence. Vanadium exerts a more powerful effect than chromium in raising the upper critical points (A_2 and A_3). Consequently vanadium steels require higher temperatures (30 to 40° C.) for hardening and annealing than carbon steels. Vanadium renders the coalescence of the pearlite and cementite much more sluggish and, therefore, promotes the formation of globular or sorbitic pearlite in the normally cooled steels. On account of this tendency, also common to the chrome steels, vanadium steels are much tougher than carbon steels of like strength. Vanadium also raises the temperature to which a steel may be heated without material loss of strength and hardness (~~Art.~~ 815–819). This latter property renders vanadium a useful alloying element in high-speed steels.

Experiments by McWilliam and Barnes * on 0.2 per cent vanadium steels show that the tensile strength of untreated steels varied directly from approximately 85,000 to 157,000 lb. per sq. in. as the carbon content increased from 0.09 to 0.71 per cent. The elongation in 2 in. was reduced from 23 per cent with 0.09 per cent carbon steels to 9.5 per cent with 0.98 per cent carbon steels. When quenched from 850° C. and tempered at 400° C. the strength increased from 61,000 to 208,000 lb. per sq. in. as the carbon content was raised from 0.09 to 0.98 per cent. The ductility of the treated steels was reduced from 33 to 11 per cent for the same increase in carbon. The yield point of these steels ranged between 75 and 85 per cent of the ultimate strength. Carbon beyond 1 per cent does not appear to benefit the strength of vanadium steels.

Vanadium steel is used to some extent in making castings for locomotive frames, for forgings, automobile axles, springs and battering tools. The ternary vanadium steels have been displaced very largely, however, by the superior chrome-vanadium steels.

734. Silicon Steels.—Owing to difficulty in rolling, steels containing more than 5 per cent silicon are not of commercial value. The influence of silicon on the mechanical properties of steel is similar to that of carbon but is proportionately much less powerful. Hadfield * found that the effect of silicon in increasing the strength of unannealed steel rose from 8000 lb. per sq. in. for 1½ per cent silicon to 27,000 lb. per sq. in. for 3½ per cent silicon. In his experiments the elastic ratio varied between .73 and .80 and the elongation in 2 in. decreased from 31 to 14 per cent with increase of silicon from 1½ to 3½ per cent. By alloying silicon with pure iron, Yensen † found that the strength was increased from 38,000 to approximately 85,000 lb. per sq. in. as the silicon content was increased from 0 to 4 per cent.

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* *Jour. Iron and Steel Inst.*, Vol. 83, p. 294.

Steels with silicon above oxidation requirements are sometimes used for long span bridges, for springs and in sheets for electrical purposes. Structural silicon steels containing carbon 0.25 to 0.35, manganese 0.65 to 0.85, and silicon 0.25 to 0.30 per cent exhibit tensile strengths of 80,000 to 95,000 lb./in.^{2}, yield points of 45,000 to 60,000 lb./in.^{2}, and elongations of 20 to 25 per cent in 2 in. For automobile gears and springs silico-manganese steels containing carbon 0.40 to 0.50, manganese 0.50 to 0.70, and silicon 1.25 to 2.00 per cent, after suitable heat treatments, attain tensile strengths of 200,000 lb./in.^{2} with elongations of 8 to 10 per cent in 2 in. Silico-manganese steels are less expensive than the chrome-nickel or chrome-vanadium steels, but are less tough and are subject to decarbonization in heat treatment.

On account of cheapness, low energy losses, and high permeability to magnetism, steels containing up to 4 per cent silicon with carbon and manganese low are used for pole pieces of dynamos and for transformer cores.

735. Chrome-nickel steels constitute one of the most important classes of alloy steels. The properties rendering these steels of high commercial value are very high strength, elastic limit and hardness combined with good ductility, and a high degree of toughness, all of which may be secured by proper heat treatment.

The most valuable steels of this class are those which are normally pearlitic, those containing pearlite and ferrite ($C<0.85$ per cent) being used much more than steels containing pearlite and carbide ($C>0.85$ per cent). In the commercial chrome-nickel steels the composition ranges are about as follows:

Type	Cr	Ni	C	Mn	Si	P	S
Low......	0.5–0.7	1.0–1.5	.20–.40	.50–.80	Low	< .04	< .04
Medium...	0.9–1.2	1.5–2.0	.20–.50	.30–.60	Low	< .04	< .04
High....	0.7–1.8	2.5–3.5	.20–.50	.50–.70	Low	< .04	< .04

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* *Jour. Iron and Steel Inst.*, Vol. 2, p. 212.

† *Bull.* No. 83, Engr. Expt. Sta., Univ. of Illinois.

Bullens * says that the most effective ratio of nickel to chromium is approximately 2½ to 1.

In steels of the above composition it appears that the influences of nickel and chromium on strength are cumulative. In comparing with nickel steels of like strength the quaternary alloys have greater hardness and higher elastic limit due to the presence of chromium; furthermore they are somewhat less costly. Again comparing with the chrome steels of equal strength, it appears that the chrome-nickel steels are less hard and have a somewhat lower elastic ratio but are much tougher, more ductile and less liable to injury through overheating than the former.

Bullens states that the critical range of these steels is lower than for carbon steels and suggests the following as a suitable method for heat treating gear stock of chrome-nickel steel:

" (1) Quench in oil from 175 to 200° F. over the critical range.
" (2) Quench in oil from about 50° F. over the critical range.
" (3) Anneal at about 75° F. under the critical range.
" (4) Machine.
" (5) Quench in proper medium from about 50° F. over the range.
" (6) Draw the temper to suit the work in hand."

For shafting and axles requiring a toughening treatment the above set of operations may be abridged by following operations (1) and (2) with a drawing treatment at 900° F.

The effects of drawing temperature on the mechanical properties of a low-carbon low-chrome-nickel and a medium-carbon low-chrome-nickel steel are shown in Fig. 5. The strength and ductility of steels containing larger percentages of chromium and nickel are practically the same as those of low-chrome-nickel provided the carbon content is constant. Bullens claims, however, that the dynamic and endurance properties of the high-chrome-nickel steels after heat treatment are materially superior to those of the low-chrome-nickel varieties.

Chrome-nickel steels are much used for automobile shafts and gears, also for large axles and shafts. Rails and track bolts made of steel smelted from the Mayari ores of Cuba, which contain enough of the elements to form a low-chrome-nickel steel, have given very good service.

On account of the very fine case which these steels will take and the great toughness of the high-chrome-nickel they have been considerably used for heavy armor plate. With suitable heat treatment these steels are also used for medium armor plate, for protective decks and projectiles. For armor plate and projectiles a tenth of a per cent of vanadium is often introduced into the chrome-nickel steel.

736. Chrome-vanadium and Chrome-molybdenum Steels.—Chrome-vanadium steels have acquired extensive recognition on account of their excellent mechanical properties, uniformity in structure, simplicity with which they can be heat treated, ease of machining and soundness of the cast metal. The composition, of chrome-vanadium steels used for structural purposes generally varies between the following limits: carbon, 0.20 to 1.0; chromium, 0.75 to 1.25; vanadium, 0.12 to 0.25; manganese 0.40 to 0.75 per cent, with silicon, phosphorus and sulphur low. For many structural purposes the carbon is held between 0.20 and 0.30, chromium near 1.0, and vanadium about 0.15 per cent.

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* *Steel and Its Heat Treatment*, p. 308.

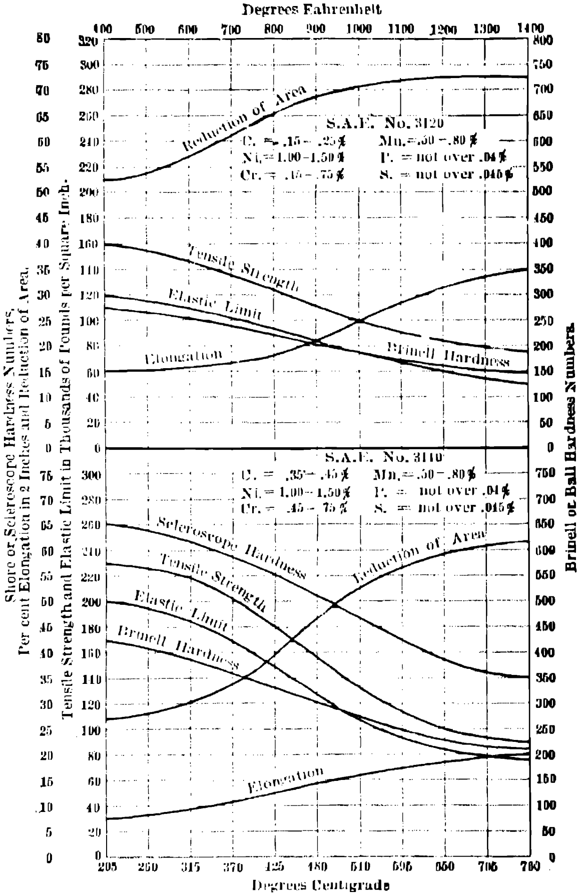

FIG. 5.—The Effect of Drawing Temperature on the Strength, Ductility and Hardness of Chrome-Nickel Steels.

Values are average minimum, excepting hardness values which are average, applying to round specimens $\frac{1}{2}$ to $1\frac{1}{4}$ in. in diameter. No. 3120 were heated to 1585–1615° F., No. 3140 to 1485–1515° F., for 15 to 30 min., quenched in oil, reheated for 30 min. at temperatures indicated, and air cooled. (From Adopted Report of Standards Committee of Soc. of Automotive Engr. See *Trans.* Vol. 11, p. 18–20.)

The low chrome-molybdenum steels containing chromium, 0.5 to 1.0, molybdenum, 0.2 to 0.5, and carbon 0.25 to 0.55 per cent, when properly heat treated, exhibit high toughness, depth hardness, and machinability. They also show low creep at high temperatures. Use is made in airplane tubing and automobile parts.

Both these ternary alloy steels have higher critical ranges on heating and lower on cooling than the common steels of like carbon contents. Both types have high strength and hardness at relatively high temperatures. The steels containing molybdenum appear to be somewhat superior for use in thick heat-treated parts where depth hardening is of importance.

The excellent strength, hardness, and ductility of certain chrome-vanadium steels after different tempering treatments are typified by the results plotted in Fig. 6. The test-pieces used by Griffiths in these experiments were ½ in. in diameter over the standard 2-in. gage length with a total length of 18 in. With larger sections the strengths and hardness of steels of like compositions would be less and the ductilities greater.

Untreated chrome-vanadium steels are sometimes used for castings and shafting. For automobile springs and gears the steels are quenched and drawn. Chrome-vanadium steels may be readily case hardened, taking a glassy hard surface with a very fine-grained tough core. This property renders them valuable for dies and bearing raceways.

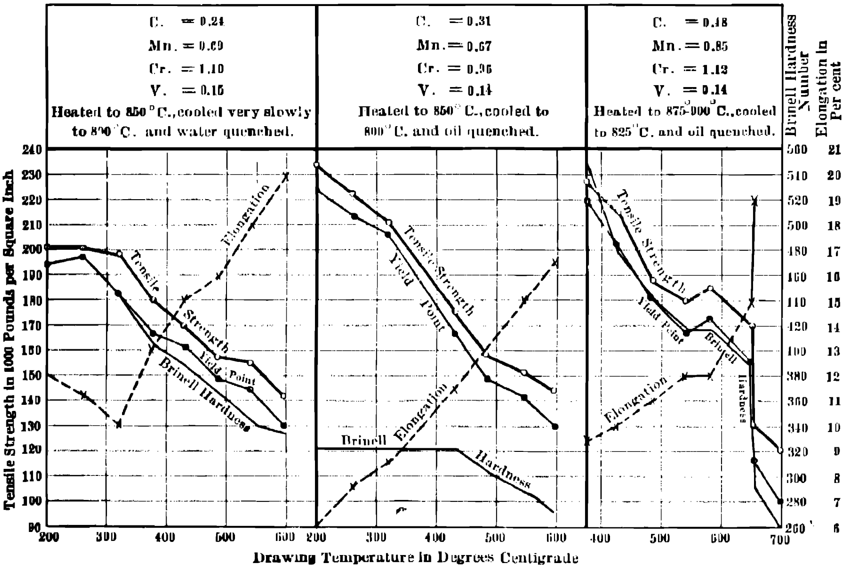

Fig. 6.—The Effect of Drawing Temperature on the Strength, Ductility and Hardness of Chrome-Vanadium Steels. (Griffiths, *Proc. A. S. T. M.*, Vol. 17, p. 37.)

737. High-speed Steels.—One of the greatest advances in promoting rapid machining of metal parts has come about within the past forty years through the introduction of steels for tools which can cut four or five times as rapidly as the simple carbon steels. Most of these steels can be run at a red heat without losing their hardness. In fact, many work to best advantage only when run at high temperatures and high speeds.

Most high-speed steels contain from 15 to 20 per cent of tungsten, 3 to 5 per cent of chromium, 0.5 to 2.0 per cent of vanadium, 0.60 to 0.80 per cent of carbon with silicon, sulphur, and phosphorus running low. Tests at Watertown Arsenal indicate that high-speed steels of lower cost suitable for certain types of use can be made by replacing tungsten in the above analysis with 9 or 10 per cent of molybdenum. Cobalt, because of its hardening effect at red heat, is also added to high-speed steels, usually in amounts from 3 to 5 per cent. Although the critical points and the changes in constitution which the high-speed steels undergo in heat treatment is still largely a matter for further research to settle, there appears to be evidence,* however, that at temperatures near the melting-point the carbon is in combination with the tungsten and chromium as a double carbide of these elements, but if the steel is slowly cooled the carbon combines with the iron at lower temperatures. What changes in constitution are effected by the introduction of vanadium is not known. It seems likely that it also forms carbides like chromium and tungsten.

By cooling these steels rapidly from a temperature near the melting-point, approximately 1250° C., down to a temperature below the ordinary critical range of the carbon steels, it is possible to retain the carbon in combination with the tungsten and chromium and to prevent the formation of the carbide of iron. Since these carbides impart great hardness and are very stable for all ranges of temperature up to a red heat, it follows that steels in which they are the essential components will retain their hardness at much higher heats than carbon steels in which hardness is conferred by the unstable carbide of iron.

The heat treatment generally given high-speed lathe and planer tools consists in heating to incipient fusion in a non-oxidizing atmosphere and quenching in an oil bath. For milling cutters and tools of accurate form, the quenching temperature is made slightly less to avoid injury to the shape of the tool. Where considerable toughness must be imparted, tools are quenched in molten lead and air cooled, or reheated in molten lead after oil quenching and air cooled. High-speed steels may be annealed by soaking for a long time at a temperature just above the critical range of carbon steels. So treated they possess high strength and good ductility.

Aside from tools, high-speed steels are also used in parts which must withstand high heat and wear, as in the exhaust valves of gas engines, and in dies through which brass is extruded.

Tungsten carbide has also been developed, trade names—Carboloy, Widia, and Dimondite—to form the cutting edges of tools operating at high speeds (see *Mech. Engr.*, Vol. 51, p. 596). Though very costly, tests indicate that these tools may be efficiently used at high speeds for small cuts on low-tensile strength materials like malleable and cast iron. Under such conditions tool edges made of this alloy wear two to four times as long per grind as other tools. Brittleness militates against its use for rough turning or where the tool is subjected to pronounced vibration.

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* Carpenter, H. C. H. in *Jour. Iron and Steel Inst.*, 1905, Pt. 1, p. 433; also Edwards, C. A., in *Jour. Iron and Steel Inst.*, 1908, Pt. 2, p. 104.

CHAPTER XXV

CAST IRON AND MALLEABLE CAST IRON

CAST IRON

738. Importance of Cast Iron.—On account of cheapness, strength, ease with which it may be melted and cast into more or less intricate shapes, ease of machining, and ease with which its hardness may be varied, cast iron is the most-used of the cast metals employed in engineering constructions and machines. It is very extensively fabricated into water-pipes, cylinders, car-wheels, agricultural machinery, stoves, hardware, machine frames, bed plates, and column bases; and to a lesser extent for columns, grate bars, ornamental castings, pipe fittings, and agricultural implements. Further uses are indicated in Table 1. Where toughness is necessary cast iron is displaced by the more expensive malleable cast iron or by the still more costly cast steel. Again in constructions where the metal must withstand corrosion, brasses, bronzes and other alloys, all of which are very much more expensive than cast iron, displace it.

As an indication of the great use of cast iron, we note that about one-fifth of the pig-iron annually made in the United States is remelted and made into cast iron. From this pig iron and about a million tons of scrap approximately seven million tons of gray-iron castings are produced.

MANUFACTURE OF CAST IRON

739. Remelting of Pig Iron.—Although pig iron from the blast furnace is sometimes molded into final form, most of the pig iron used for castings is remelted before being molded into final shape. Remelting is necessitated by the variability in the pig iron run from a given furnace, by the difficulty of adjusting the composition of the molten iron, and by the necessity of mixing different grades of pig iron in order to secure the desired grades of castings.

Most of the ordinary gray iron used in machine parts is remelted in the cupola, the better grades of gray iron—often called gun iron—and the white iron used in making malleable cast iron are generally remelted in the air-furnace. Some use has also been made of small open-hearth furnaces and considerable use of electric furnaces to remelt pig iron for high-grade cast iron and malleable cast iron.

The function of the remelting furnace is simply to produce homogeneity in the charge which has been proportioned with reference to the use of the product. Changes between the average composition of the metal charged and that of the castings are, in general, small although sometimes important.

740. Materials Charged.—Compositions of the pig irons commonly used in smelting cast iron are given in Art. 582. In many parts of the country the chemical analysis of the pig iron serves as means of grading it and purchase is made on this basis. Generally the silicon content is specified and the sulphur limit prescribed. Some foundrymen still rely on the character of fracture exhibited by the pig iron as a criterion of composition. Special pig irons containing high percentages of silicon, the Scotch irons and ferro-silicons, are sometimes added to soften the iron; while others containing high percentages of manganese, ferromanganese, for example, are used as hardeners.

Besides pig iron, from a tenth to a half of the metal charged consists of the refuse from previous heats and whatever old machinery or parts of cast iron the foundrymen can purchase. All of this heterogeneous mass is termed scrap. On account of variability in its composition the proportion of scrap is generally less than 25 per cent of the metal charged when the best grades of castings are being made.

Coke is the fuel most commonly used in the cupola, bituminous coal in the air-furnace. Under favorable conditions with large furnaces the ratio of fuel to iron is about 1 : 8 or 1 : 10 for the cupola and 1 : 4 for the air-furnace.

A flux consisting of crushed limestone or other form of lime carbonate is sometimes added in very small amounts to slag off the earthy impurities and reduce the sulphur content of the cast iron.

741. The cupola is a sort of small blast furnace. It consists of a vertical cylindrical steel shell of nearly uniform diameter lined with fire-brick. Fig. 1 shows an elevation of a cupola. At the bottom is placed the hearth or crucible which extends upward a short distance to the level of the tuyeres. At the bottom of the hearth is located the taphole and opposite

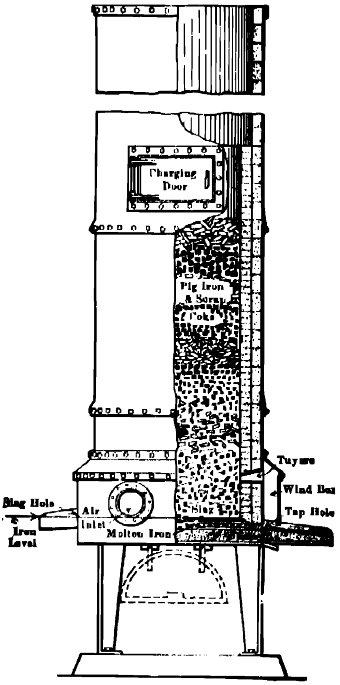

FIG. 1.—Cupola.

to it several inches above the bottom is the slag-hole. The tuyeres are placed in one or two circumferential rows. Air at a pressure of 1 lb. per square inch or less is served to the tuyeres through the wind box which surrounds the hearth. Above the tuyeres is the melting zone which is surmounted by the stack, a door for charging being placed in the latter. Cupolas vary in internal diameter up to 10 ft. The common sizes are from 4 to 6 ft. in diameter with their charging doors 12 to 25 ft. above the hearth bottom. Cupolas of these sizes will run from 10 to 20 tons of metal per hour.

In operating a cupola, kindling is first placed on the hearth and a thick layer of coke on top of it. Alternate layers of pig iron mixed with scrap and layers of fuel are then dumped in until the stack is filled to the level of the charging door. If flux is used it is charged immediately after each layer of metal. After the fire has been kindled and the bed of fuel well ignited the blast is turned on, and in about ten minutes molten iron trickles from the tap-hole. The tap-hole is then closed with a plug of fire-clay. As the slag accumulates it runs off through the slag-hole and from time to time the iron is tapped into a large ladle. Ordinarily a cupola is charged and discharged several times a day, but at some plants they are run continuously for several days. The necessity of repairing the lining at frequent intervals prohibits long runs.

During the melting process a small amount of iron and 0.2 to 0.3 per cent of silicon is oxidized, while 0.05 to 0.10 per cent of sulphur and, under certain conditions, a little carbon is absorbed from the fuel.

742. The air-furnace is somewhat like the puddling furnace used in making wrought iron, but larger in size (Fig. 2). At one end it is provided with a fire-box and at the other a stack; between is a shallow rectangular hearth, served by a door in the side. Separating the hearth and the fire-box is a low vertical wall called the fire-bridge. The opposite end of the hearth is formed by the flue-bridge which rises to the same height as the fire-bridge. Air-furnaces range in capacity from 5 to 40 tons.

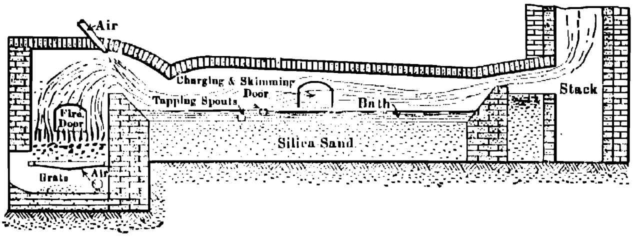

Fig. 2.—Showing Principle of Air-furnace.

Before the charge is introduced into the furnace the bottom of the hearth is covered with an even layer of sand; then the scrap and pig iron are placed upon it. The furnace door is sealed with clay and the fire started. Melting of the iron is accomplished principally through radiation from the sloping roof and, in part, through the heat of the hot gases which sweep over the hearth. During the melting process the bath is rabbled occasionally with iron bars to promote uniformity in melting and in composition. If much slag forms on the bath it is partially skimmed off to raise the temperature and promote oxidation of the carbon and silicon. In order that the top metal, which is the hottest, may be run from the furnace, tapping is done through a set of holes placed at different elevations in the hearth. The usual rate of producing iron with the air-furnace is 3 to 4 tons per hour.

743. Comparison of Cupola and Air-furnace Processes.—The cupola process is quicker, cheaper in installation and in operation; the metal is hotter and more uniform in temperature— conditions which mean much in casting; the loss of metal through oxidation is also less than in the air-furnace. On the other hand the air-furnace produces a larger quantity of high-grade iron at a single tapping. The metal in the air-furnace not being in contact with the fuel absorbs neither sulphur nor carbon. The air-furnace process is under better control and permits better regulation in the composition of the iron. In neither process, however, has there been a successful attempt at utilization of the latent heat in the escaping gases.

MOLDING

744. Patterns of the castings are made either of wood coated with shellac or metal. Wood is largely used when only a few castings are desired. When the number of castings is to be great, it is preferable to use a brass pattern and thus avoid imperfections likely to be found in the castings due to damaging of wooden patterns. If a number of castings of similar shape are to be made it is customary to join several patterns in such way that they may be poured simultaneously. Such patterns are said to be gated. Patterns are always made larger than the casting to allow for contraction in cooling. For ordinary gray cast iron an allowance of an eighth-inch per foot is a common rule. White cast iron and steel shrink double this amount; brass and copper about 50 per cent more and lead and zinc two and one-half times as much as gray cast iron. The fundamental considerations in designing a pattern are: (1) make the pattern of such shape that it may be removed from the sand without damaging the mold, if of intricate shape it may be necessary to make the pattern in two or more parts; (2) use fillets of large radius at all sharp angles and corners and thus avoid planes of weakness arising from the crystallization of the metal; * (3) avoid joining heavy and light sections wherever possible, since these parts, cooling at unequal rates, will be highly stressed at their junction (if such design is necessary some provision should be made for rapidly cooling the heavy section); (4) when possible avoid shapes where the ends of the casting will be rigidly held by the mold and contraction stresses or checking thus produced in the intermediate parts of the casting.

745. Cores.—When it is necessary to make a hollow casting some sort of core is used. This is located in proper place in the mold by projecting fins which rest in core prints that are made by corresponding projections of the pattern. If the core is of such size or shape that it cannot be held in place by core prints, iron supports called chaplets are placed in the mold. Generally cores must be so made that they will offer little resistance to shrinkage of the metal and will not burn on to the iron. They are commonly molded of dry sand mixed with flour, molasses, linseed oil or patented compound and baked in an oven. Sometimes green sand cores are used. When it is particularly necessary to avoid all stressing of the casting, cores are made with centers of crushed coke or of pipe wound with hay rope, the outside being of sand. Cores are vented to permit the escape of gases generated in pouring.

746. Materials for Molds.—Not only must the material composing the mold retain the metal and give it a smooth and true surface but it must also be sufficiently porous to allow the escape of air and gas. Sand is the most refractory cheap material for this purpose. A good molding sand generally contains not less than 80 per cent silica and 5 to 10 per cent of alumina. The higher the temperature of the molten metal, the more refractory must the sand be. Consequently the silica content must be higher for steel than for cast-iron castings. Some alumina, however, is needed to furnish requisite cohesiveness in the sand. Small proportions of magnesia, lime and iron oxide are usually present also in molding sands. More than 2 or 3 per cent of the carbonates is objectionable owing to the gas formed in calcination of them, while metallic oxides render the sand less refractory. Another important factor which affects the cohesiveness and the porosity of molding sand is the gradation in sizes of particles. The smoothness of the surface of the casting is also affected by the fineness of the sand grains. Therefore, molding sand is generally screened through a 20-mesh sieve, the gradation in sizes below that opening being determined by the work in hand.

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* When a metal cools the crystals form perpendicularly to the surfaces. If a corner is left sharp there will be a plane of separation between crystals bisecting the angle at he corner. Since the cohesion across these planes is less than in the crystals, a pronounced weakness is thus produced. Fig. 3 shows such planes for a square bar. By rounding the corners interlocking of the crystals is promoted and a stronger, more homogeneous casting is obtained.

Parting sand is a highly refractory sand which cannot be rendered cohesive by the addition of water.

Facing materials are shaken over the pattern or surface of the mold to prevent the sand from being burnt and to make the castings leave the mold freely, thus preserving a bright surface and avoiding expense in cleaning. Fine soft coal, graphite, charcoal and talc are among the substances which are mixed with six to fifteen times as much fine molding sand to make facings.

Loam is the name for a soil carrying a high content of silicious sand, considerable clay and more or less decayed vegetable and animal matter. The term is also used to designate artificial mixtures made of sand and clay with some sawdust or rye meal.

747. Molds.—The kind of castings and the number, size and shape determine the character of the molds. The common types of molds are green-sand, dry-sand and loam molds. Besides these, cast-iron molds are considerably used when a permanent type of mold is desired.

Green-sand Molds. The pattern is surrounded by a flask of wood or cast iron which serves to hold the sand in place. Generally the flask consists of two, sometimes three or more, rectangular frames of equal size which may be doweled or locked together to form a bottomless box. In molding many simple objects, half of the pattern is bedded in the lower frame, called the drag, and the other half is covered by the upper part of the flask, called the cope. The procedure is to place the drag on a mold board bottom-side up with the pattern or portion of the pattern resting on the mold board. Molding sand moistened with sufficient water to render it coherent is rammed about the pattern and several small vent holes are punched through to the pattern. A bottom board is put over the drag and the drag is turned over. The remainder of the pattern is inserted and a bit of parting sand is sifted over the top of the drag, the pattern being kept clean. Next, the cope is put in place and plugs for the runner * and riser * are properly located. Molding sand is tamped about the pattern and vents provided. The plugs are then withdrawn, the cope carefully lifted and gates from plugs to pattern are cut. A draw spike is attached to the pattern, and tapped until the pattern can be removed. After the loose sand has been removed a facing may be smeared on the surfaces of the mold; the cope is then placed on top of the drag and locked in position for pouring.

Green-sand molds are much used, especially for articles of like shape, because they can be rapidly made at low cost. When there is a large demand for a certain type of casting, molding machines are frequently used.

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* A runner is the canal through which the molten metal is poured. It is provided with a basin at the top and a hole at the bottom connecting with the mold called a gate. A riser is a vertical canal leading from the mold to the top of the cope. It serves to vent the mold, supply metal as the casting cools, and to carry off dirt.

Dry-sand molds are fashioned in iron flasks in much the same way as those of green sand. A rather coarse loamy sand is used and the molds are dried at 300 to 400° F. After baking, the surface of the mold is generally coated with a wet mixture of graphite, or charcoal with clay. Such molds are strong, will withstand hard usage, and, if properly vented, produce sound smooth castings. Dry-sand molds are well adapted for the production of cylinders, rolls, engine beds and other heavy castings where the pressure of the metal is great, or where a smooth wall of uniform thickness must be obtained

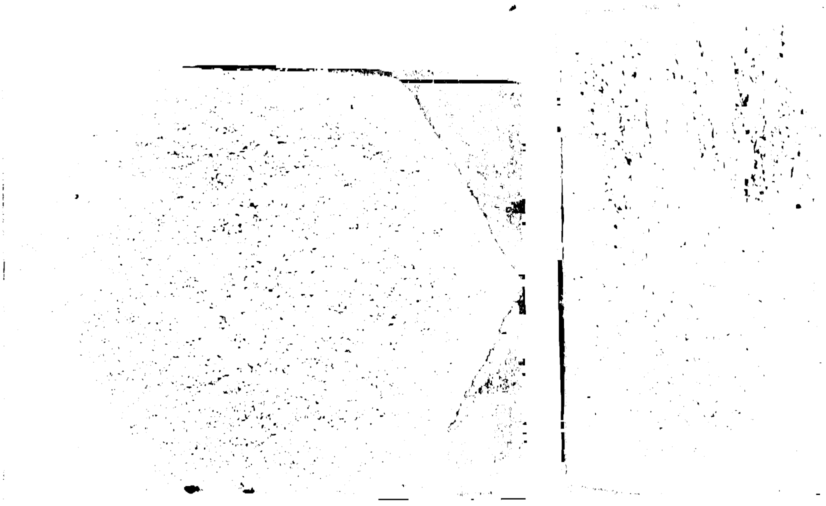
Dry-sand molds are likely to be somewhat distorted during drying and cause heavier shrinkage stresses in castings than do green-sand molds. On the other hand, castings made in dry-sand molds are more sound, smoother, and freer from inclusions of sand and dirt than those cast in green sand.

Loam molds are used principally for very large castings which are bounded by surfaces of revolution. Castings of heavy engine cylinders and fly-wheels are generally made in loam molds. The outer casing of the mold is ordinarily built of brick, sometimes of iron. To the interior of this casing dampened mixtures of loam are plastered. The surface of the mold is generated by revolving a sweep, the end of which is fashioned in conformity with the surface desired for the casting. The mold is then baked and faced. Owing to the rigidity of loam molds, provision is made during the fabrication to permit rapid destruction of certain parts immediately after the casting is poured in order that the latter may contract freely.

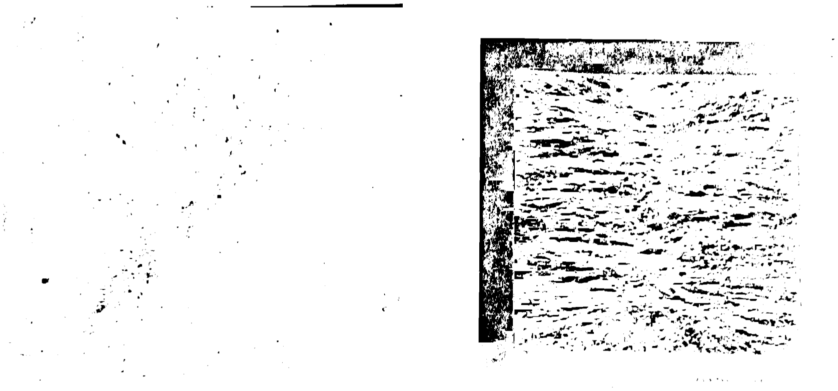
748. Chills.—Surfaces of castings which are subjected to heavy wear are made hard by rapidly cooling them in chills. Chills consist of pieces of cast iron which form the surface of the mold in contact with the part of the casting to be hardened. Sticking of the iron to the chills is prevented by coating the latter with shellac and plumbago or with a thin film of light oil. To avoid explosions resulting from contact between the molten metal and the chill, it is necessary to heat the latter to 300 or 400° F. before pouring. The treads of car wheels and the bearing surfaces of rolls are cast against chills. Changes in composition due to chilling are explained in Art. 751. Fig. 3 shows the effect of chilling on structure. The depth in inches of white iron produced by chilling is termed chill.

749. Cleaning Castings.—Flasks are removed as soon as the castings have solidified, but the pieces are generally allowed to remain in the sand until cool. Sand and dirt adhering to the surfaces of the castings are removed by rattling, by pickling in acid or by sand blasting. Rattling is done in a device similar to that used in testing the toughness of paving brick.

It can only be successfully employed on sturdy regular-shaped pieces. Rattling also produces a hard skin on the castings. Pickling is used on fragile or intricate castings and on pieces which must be machined. Dilute solutions of hydrochloric or sulphuric acid are often used for pickling, but they attack the iron. Hydrofluoric acid in a 5 per cent solution is more efficacious since it attacks the sand. Sand blasting is an effective means of cleaning heavy work.



(a) Sand-mold, not Chilled. (b) Chilled on One Side.



(c) Chilled on Four Sides. (d) Chilled on Opposite Sides.

FIG. 3.—Showing the Effect of Chilling on Car-wheel Iron. (*Jour. Frank. Inst.*, April, 1897.)

COMPOSITION AND CONSTITUTION

750. The Principal Constituents.—Cast iron is really unrefined steel contaminated with larger proportions of impurities. As in the carbon steels, the five main impurities in cast iron are carbon, silicon, sulphur, phosphorus and manganese. They constitute from 5 to 8 per cent of cast iron, by weight. In addition to these elements, in making alloy cast irons one or more of the following elements is added—nickel, chromium, molybdenum, vanadium, titanium, and copper.

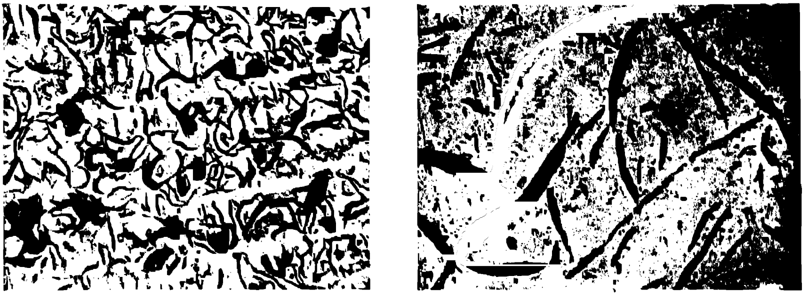
Since the properties of cast iron are dependent principally upon the proportion of the different impurities and the combinations which they form in the iron, the influence of each of the essential constituents will be considered. Owing to the variety of forms and combinations in which carbon is found in cast iron (see Art. 659 and 662), the influence of this element is of the most importance in determining the properties and the value of the iron. Thus we find three main types of cast iron—gray, white, and mottled iron—which owe their characteristics and properties to variations in the form of carbon content.

751. Carbon in Cast Iron.—The proportion of carbon in cast iron generally lies between 2½ and 4 per cent by weight. Carbon, as has been shown in Art. 662, occurs in two forms—either free as graphite, or chemically combined with the iron as iron carbide (Fe_3C). When free, the proportion of the volume of the metal occupied by the graphite, due to its specific gravity being much less than that of iron, is about 3.2 times as much as the percentage by weight. Therefore the spaces occupied by the flakes of graphite aggregate 8 to 13 per cent of the bulk of the iron. When the carbon is combined with the iron the proportionate bulk of the iron carbide is still greater, being over fifteen times the percentage of combined carbon.

The amount of carbon which the molten iron will retain in solidifying is dependent upon the composition of the iron. Again the proportion of the carbon which is retained in combined form is influenced greatly by the presence of other elements and by the rate of cooling. Thus by adding manganese or chromium the solubility of carbon in iron is increased and much of it is combined with the iron. On the other hand, additions of silicon or aluminum reduce the solubility of carbon in iron and promote the formation of graphite. Rapid cooling tends to cause combined carbon, slow cooling furthers increase in graphite. When the composition is properly adjusted it is possible to retain the carbon as carbide of iron by rapid cooling or to precipitate it by slow cooling.

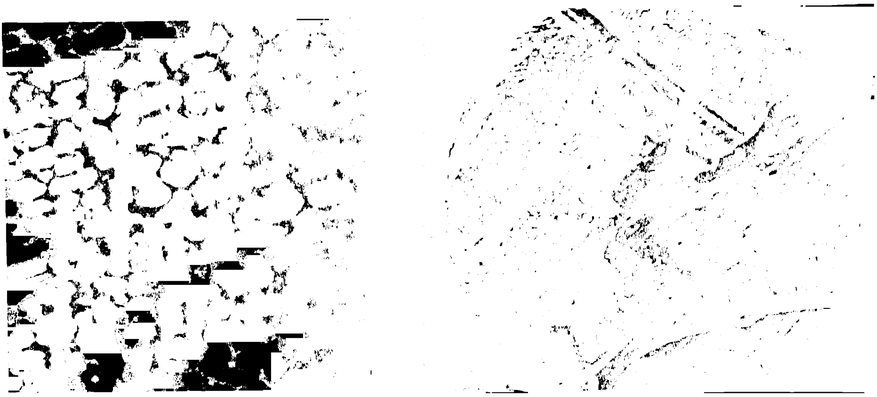
If in cooling the carbon is largely precipitated, more or less uniformly in the form of graphite flakes, the iron is soft and presents a dull gray fracture which is brightened here and there by glistening iron crystals.

This is **gray cast iron.** When the carbon is retained in combined form, the cast iron is very hard and brittle; and the silvery white fracture has led to the name, **white cast iron.** In some irons the major portion of the carbon is retained in the combined form while a lesser part is precipitated as graphite. Such irons exhibit a white fracture spotted with dark gray patches and are termed **mottled cast irons.** Photo-micrographs of gray and white cast irons appear in Fig. 4.



(*a*) Gray Cast Iron with finely divided graphite more or less globular in form (×50). (Aston.)

(*b*) Gray Cast Iron with graphite in large flakes (×50). (Harbison Walker Refractories Co.)



(*c*) White Cast Iron. The white constituent is cementite and the dark one is pearlite (×100). (Storey.)

(*d*) White Cast Iron under higher magnification (×500); showing lamellar pearlite (banded structure), flakes of graphite, and cementite. (Whst.)

FIG. 4.—Photomicrographs of Gray and White Cast Irons.

From the foregoing it follows that irons containing large amounts of manganese or chromium are likely to be permanently white while those having a high silicon content are gray. With proper adjustment in composition, cast iron may be rendered white by cooling rapidly or gray by cooling slowly from the molten state.

The proportion of carbon and its form influence more or less most of the physical and mechanical properties of cast iron. The melting temperature is reduced as the carbon content or the percentage of combined carbon is increased.* Therefore white cast iron has a lower melting-point than gray iron, but it is less fluid when molten. Shrinkage varies inversely as the carbon content, but white iron shrinks nearly twice as much as gray iron. The specific weight of gray iron increases with the decrease in carbon content and varies from 425 to 450 lb. per cubic foot. White cast iron is heavier than gray due to the chemical combination of the carbon and weighs in the vicinity of 475 lb. per cubic foot.

The influence of the proportion of combined carbon on the constitution and mechanical properties of cast iron containing 4 per cent of carbon is idealized in Howe's diagram in Fig. 5.† Other factors constant, the tenacity of the whole varies with the proportion of pearlite in the matrix and is a maximum, as in normally cooled steels, when the matrix contains 1.2 per cent carbon. The hardness varies with the proportion of cementite in the matrix. The diagram also shows the influence of combined carbon on machining qualities, properties, and general uses of cast iron. Irons with carbon contents of 2.75 to 3.25 per cent are preferred to the one illustrated because the weakening influence of the graphite is less, the strengthening effect of the matrix greater, and the castings can be made more sound and free from defects.

Mechanical properties of cast irons are affected not only by the proportion of graphite but also by the size and dispersion of the flakes. The tenacity and toughness of cast irons containing fine, rounded, graphite particles uniformly dispersed, Fig. 4*a*, are superior to the same properties for similar irons with coarse flakes, Fig. 4*b*. Hence melting at high temperatures (above 1500° C.), which is attended by obliteration of existing non-metallic nuclei, effectively reduces the size of flakes and thus promotes superior mechanical properties.

752. Silicon in Cast Iron.—Next to carbon, silicon exercises the most important influence on the properties of cast iron. It combines with the iron, forming iron silicide, which in turn is dissolved in the ferrite. The proportion of silicon in cast iron usually runs between 0.5 and 3.0 per cent, although certain special castings for acid containers are made with a much higher silicon content. Silicon in small percentages increases the fluidity of the molten iron, decreases blow-holes and increases the density of castings. Silicon also reduces the solubility of carbon in iron. According to Wust and Peterson, each percentage of silicon throws out of solution 0.27 per cent carbon, consequently by decomposing the hard cementite, it acts as a softener and also decreases shrinkage. However, when present in excess of the amount required to decompose cementite, the direct hardening influence of iron silicide becomes noticeable; and with 5 or 6 per cent of silicon the iron is hard and has a mirror-like fracture. In short, by varying the silicon content the foundryman exercises a most important control over a wide range in the properties of cast iron.

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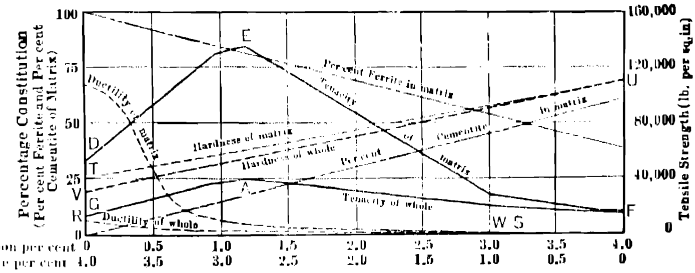
* Porter in *Trans. Am. Foundrymen's Assoc.*, Vol. 19, p. 113, states melting temperature in $F° = 2175 - 62.5C$, where C = per cent combined carbon (less than 3.5).

† *Proc. A.S.T.M.*, Vol. 2, p. 252.

The combined influence of carbon and silicon upon the structure of cast iron is well illustrated in Fig. 6.* The manganese in all of the test heats ranged from 0.25 to 0.35; sulphur averaged about 0.06 and phosphorus from 0.13 to 0.18 per cent. Cylindrical specimens 2 in. in diameter and 12 in. long were poured in green-sand molds with proper regard for disturbing influences due to variations in pouring temperatures. They were cooled in the molds two hours before quenching in water. In the diagram, the line *G–G* represents limiting combinations of silicon and carbon at which the test-pieces were gray. The line *M- M* shows the varying combinations of carbon and silicon producing a mottled fracture, while the line *W–W* represents the boundary for white fractures. For smaller

Name of matrix	Low carbon steel	Medium carbon steel	High carbon steel	White cast iron	
Name of the cast iron i.e., of the whole	Very open gray or very graphitic cast iron		Close gray cast iron	Mottled cast iron	White cast iron



Strength	Weak	Strongest		Weak
Ductility	Least brittle			Most brittle
Hardness	Softest	Soft	Harder	Hardest
Because of its strength and ductility the iron is suited to uses in which it will have to undergo or resist	shock	moderate shock the iron is suited to most engineering purposes		no shock unless metal is strongly supported
Because of its hardness the iron is suited to uses in which it will have to undergo or resist	much machining in preparation but little abrasion in use	moderate machining in preparation not excessive abrasion in use		no machining in preparation, much abrasion in use

FIG. 5.—Influence of Carbon on Constitution and Properties of Cast Iron. (Howe.)

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* G. M. Thrasher in *Met. and Chem. Engr.*, Vol. 13, p. 40.

test-pieces or for more rapid rates of cooling these lines would be shifted upward to the left; for larger test-pieces or for slower cooling the lines would be displaced toward the lower right corner of the diagram.

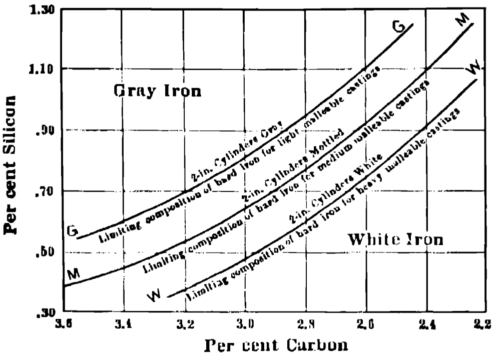


Fig. 6.—Relation of Carbon and Silicon Contents to Structure of Cast Iron under Normal Cooling. (Thrasher.)

The influence of silicon on the mechanical properties of irons containing about 2 per cent total carbon is well shown by Fig. 7. These experiments were very carefully made on specially prepared irons under the direction of Thos. Turner, Associate of Royal School of Mines, England. The hardness tests were made by a sclerometer, the weight necessary to produce a scratch of given width with a standard diamond point being the criterion of relative hardness. Fig. 7 shows that maximum hardness and crushing strength obtained when the castings were rendered sound and the per cent graphite was a minimum, per cent silicon being about 0.80 per cent for the iron tested. Further increase in silicon to 1 per cent produced maximum stiffness, when increased to 1.4 per cent maximum transverse strength resulted, at 1.8 per cent the greatest tensile strength obtained, and at 2.5 per cent silicon the maximum softness. Increasing the silicon beyond 2.5 per cent caused an increase in hardness and brittleness.

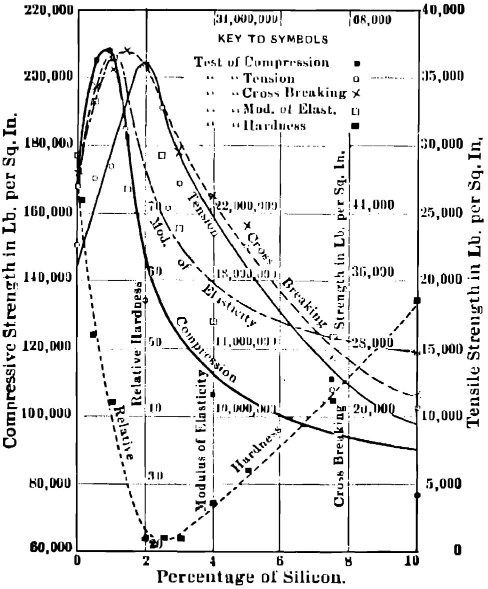


Fig. 7.—Influence of Silicon on Mechanical Properties of Cast Iron. Specimens were $1\frac{1}{8}$ in. in diameter and were tested with skin on. (From Turner's *Iron*.)

The very important influence of silicon in reducing shrinkage is well brought out in Fig. 8, showing results of W. J. Keep. From other data by Keep, Fig. 9, which shows the variation in transverse strength for different sizes of bars and different silicon contents, has been prepared. The data emphasize the necessity of testing bars of the same thickness as the finished casting, if a knowledge of the strength of the metal in the casting is wanted.

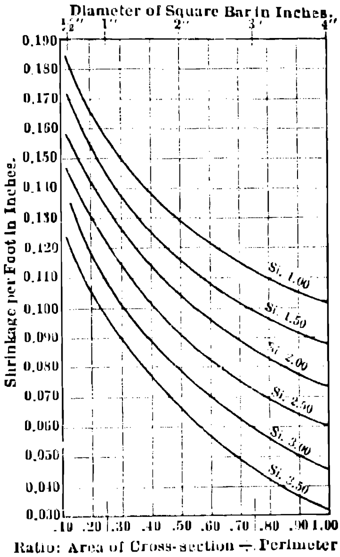


FIG. 8.

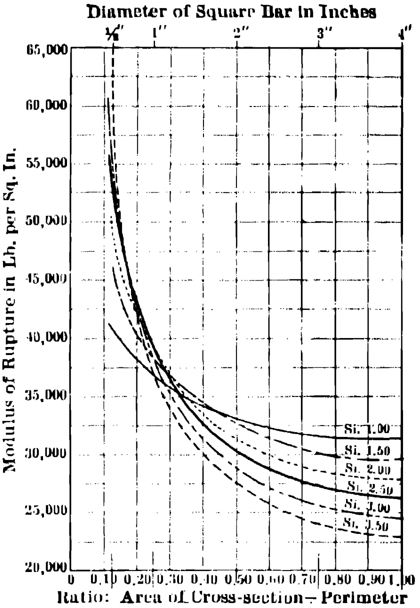


FIG. 9.

FIG. 8.—Influence of Silicon on Shrinkage of Cast Iron Specimens of Various Areas of Cross-section. (Keep.)

FIG. 9.—The Variation in Cross-breaking Modulus of Rupture of Cast Iron for Different Sizes of Bars and for Varying Percentages of Silicon. (Keep.)

753. Sulphur in Cast Iron.—Sulphur is an undesirable element in cast iron and is generally limited to less than 0.1 per cent. Since it is believed to promote the formation of combined carbon the above limit is often doubled on irons cast in chills. It combines with manganese to form the sulphide (MnS) or, if the manganese is very low and not sufficient to satisfy the sulphur, iron sulphide (FeS) may be formed. Since these sulphides solidify at considerably lower temperatures than cast iron they tend to make castings brittle and weak at high temperatures. Sulphur in high percentages (0.5 per cent or over) also increases shrinkage and causes hard, brittle iron. These evil effects may be neutralized by proper additions of silicon.

754. Phosphorus in Cast Iron.—According to Stead, phosphorus occurs in gray iron in a eutectic of iron phosphide plus iron, and in white iron in a eutectic of iron carbide, iron phosphide and iron. These hard brittle components called *Steadite* bulk approximately 10 times as much as the weight percentage of phosphorus. When phosphorus does not exceed 0.5 per cent it has no marked effect upon cast iron. If more than 2 per cent of phosphorus is present the iron is embrittled and the strength diminished. High phosphorus irons are much more fluid and shrink somewhat less than irons low in phosphorus. High-phosphorus irons, therefore, take a good impression of the mold and are much used in making thin stove castings and ornamental castings where great strength and toughness are not essential.

755. Manganese in Cast Iron.—The proportion of manganese ordinarily found in cast iron ranges from 0.4 per cent to 1.2 per cent. When present in such proportions manganese combines with sulphur, forming manganese sulphide (MnS), and—having satisfied sulphur—with carbon to form manganese carbide (Mn_3C). The latter is found in cementite united with iron carbide. Ferromanganese is often added to the molten iron to reduce the sulphur and oxygen contents. This is accomplished by combination and partial withdrawal of the oxides and sulphides of manganese into the slag. Manganese increases the solubility of carbon in iron and opposes the liberation of graphite. Increased shrinkage and hardness are promoted by increasing the manganese content beyond that required to satisfy sulphur. Therefore manganese must be kept low in gray iron which is to be machined, while in parts which must withstand abrasion a high manganese content is desirable.

756. Other Elements in Cast Iron.—In small percentages copper is found in some ores and traces of titanium are also often present. Copper up to 1 per cent increases machinability and resistance to corrosion. Titanium in small percentages has a more powerful graphitizing effect on cast iron than silicon. From 1 to 2 per cent of nickel is sometimes added to cast iron to promote machinability, uniformity, and strength. Chromium additions up to 1 per cent are often made to increase depth of chill, hardness, and strength; in higher percentages to improve resistance to heat. Molybdenum additions up to 1.5 per cent effect potent increases in strength, toughness, and hardness. Vanadium up to 0.5 per cent promotes hardness, toughness, and depth of chill.

757. Defects in Cast Iron.—Checks, segregation, blow-holes and coarse grain, the principal defects in cast iron, originate during the cooling of the castings. Checks are small parallel cracks in the surface of a casting. They generally run transverse to the long axis of the piece. Checks may arise from errors in designing the shape of the casting or mold which prevent contraction during cooling. Irons of high sulphur content are liable to have this defect owing to their great shrinkage and lack of strength while at a red heat.

Segregation is very pronounced in high phosphorus irons, where the eutectics of iron phosphide and iron separate from the main part of the metal and form brittle masses which are more or less well connected, depending on the amount of phosphorus present. Even with smaller percentages of phosphorus there appears to be a well-marked tendency to the formation, here and there, of little knots of metal which are found attached within gas cavities. Analyses of the knots show that the phosphorus and sulphur contents are very much above the mean compositions. The sulphides are also found in greatest proportion in the top of the casting and in the parts cooled most slowly. Carbon and silicon sometimes segregate in such manner that interior portions of the metal are white and exterior parts are gray. When such segregations occur at different parts of the surface of a casting, they render it very difficult to machine. Sometimes relief of the non-uniformity can be had by annealing the piece.

Segregations make it very difficult to secure representative samples of castings for chemical analysis. Since sulphur segregates on the top of a casting, drillings should be made through the castings from the top and the sample thoroughly mixed. Variations in size of section will cause changes in the combined carbon content; more combined carbon will exist in the skin than in the interior; these conditions must all be kept in mind in locating drill holes for borings or in cutting samples from the casting.

Blow-holes are generally due to improper venting of the mold or to a high proportion of sulphur. If pronounced, they seriously affect both strength and toughness of the casting.

A coarse or open grain in the iron is caused by too slow cooling, or it may be due to a very high phosphorus content. In thick parts a coarse open grain is generally found near the center of the section (see Fig. 3*a*) and is quite difficult to prevent. A more compact structure is often secured by lowering the silicon content, by charging turnings or chips of cast iron along with the pig iron, or by adding nickel and chromium.

Besides the above-mentioned defects, spongy spots and " cold shuts " sometimes result from lack of fluidity in the iron or from improper gating. Cold shuts are fault planes in the metal produced by the solidification of part of the casting before the remaining molten metal was run into place. Spongy spots are exaggerated forms of open grain; they are often due to a solidification of metal in the risers before the interior of the casting has solidified. The interior is thus cut off from the supply of metal which is needed to fill voids caused by shrinkage in cooling, and a porous structure results.

758. Compositions Suitable to Different Kinds of Castings.—Usually the properties, such as strength and hardness, desired in castings are specified by the purchaser and the composition is left to the discretion of the foundryman. Table 1 shows compositions of irons for some uses. Whereas the major portion of gray iron castings are made without the alloying elements, nickel, chromium, molybdenum, etc., castings for severe service are frequently made with such additions. Thus nickel cast irons are used in automotive and locomotive cylinders, gears, pump bodies, and crusher frames. Cast irons containing chromium find use in chills, crusher jaws, annealing boxes, and molds for glass. Nickel-chromium cast irons have been used in automotive cylinders, forging dies, brake drums, and clutch plates. Molybdenum, promoting strength and uniformity, has been added to cast irons for brake drums, automotive cylinders, ingot molds, and other high strength castings. Vanadium cast irons have been used in grate bars, locomotive cylinders, rolls for steel mills, and molds for bottles.

TABLE 1.—COMPOSITIONS OF CAST IRONS FOR VARIOUS PURPOSES

(Should not be a basis for specifications.)

Kind of Castings.	Composition in Per Cent.								
	Total Carbon.	Combined Carbon.	Silicon.	Manganese.	Phosphorus.	Sulphur.	Nickel.	Chromium.	Molybdenum.
Agricultural machinery	3.2–3.5	0.4–0.5	2.1–2.3	0.6–0.8	<0.30	<0.10			
Ammonia cylinders	3.0–3.3	.....	1.0–1.7	0.7–0.9	<0.30	<0.10			
Automobile cylinders	3.1–3.3	0.4–0.6	2.1–2.3	0.6–0.8	<0.20	<0.13			
Automobile cylinders	3.1–3.3	.....	1.7–1.9	0.6–0.7	<0.20	<0.13	1.2–1.3		
Automobile cylinders	3.2–3.4	.....	1.7–1.9	0.6–0.7	<0.20	<0.13	1.4–1.6	0.4–0.5	
Automobile pistons	3.3–3.5	0.4	2.2–2.4	0.6	<0.20	<0.12	.....	.....	0.4
Automobile piston rings	3.3–3.6	.....	2.8–3.0	0.5–0.7	0.5–0.7	<0.10			
Brake drums	3.2–3.3	.....	1.9–2.1	0.6–0.7	<0.20	<0.12	1.2–1.4	0.5–0.6	
Car wheels, chilled	3.5–3.7	0.6–0.8	0.6–0.8	0.5–0.7	0.3–0.4	<0.10			
Crusher jaws and rolls	2.0	.....	1.0	.....	.....	.....	.....	25.0	
Drums, steam	3.3–3.4	0.5–0.6	1.4–1.5	0.8–1.0	0.3–0.5	<0.10			
Furnaces and stoves	3.6–3.7	0.5–0.6	2.1–2.2	0.5–0.6	0.6–0.9	<0.10			
Gears, heavy	3.1–3.3	0.6–0.7	1.1–1.2	0.6–0.8	0.2–0.3	<0.10			
Generator frames, steam turbines, pumps	3.2–3.3	0.5–0.6	1.9–2.0	0.5–0.6	0.4–0.6	<0.10			
Grinding balls and liners	3.0–3.5	.....	<2.0	.....	.....	.....	.....	3.0	
Heat resisting castings	3.0–3.5	.....	2.0–2.3	.....	.....	.....	.....	1.2–1.3	
Heavy forming dies	3.0	.....	1.2–1.3	0.6–0.7	<0.2	<0.10	2.6–2.8	0.7–0.9	
Pipe, centrifugally cast	3.5–3.6	0.7–0.8	1.6–1.8	0.5–0.6	0.7–0.9	<0.10			
Pipe fittings	3.0	.....	1.6–1.8	0.6–0.8	0.5–0.8	<0.10			
Rolls, chilled	3.0–3.2	.....	0.6–0.8	1.0–1.2	0.2–0.4	<0.10			
Rope drums, high-strength castings	2.4–3.0	0.6–0.7	2.0–2.2	0.6–0.7	<0.10	<0.10	1.2–1.3		

PROPERTIES OF CAST IRON

759. Shrinkage.—At the moment of complete solidification gray cast iron expands, due to the precipitation of more or less graphite from the eutectic of austenite and cementite. Since graphite occupies more space than if chemically combined in the molten metal the total volume upo solidification is greater than that of the molten metal just before solic fication. If phosphorus is high in the iron the initial expansion is soo augmented by the solidification of the phosphide eutectic which occurs at approximately 1000° C. As the temperature falls these expansions are gradually offset by contraction due to cooling. At 700° C., if the composition is suitable and the rate of cooling slow, another precipitation of graphite with consequent expansion takes place. With high silicon and high total carbon the latter expansion is very pronounced. The casting then shrinks continuously until it reaches room temperature. With proper regulation of the phosphorus, silicon and total carbon content, it is possible to avoid a coarse open-grained metal and still control shrinkage quite closely. Fig. 8 indicates the variations in shrinkage due to changes in silicon and size of casting.

A simple shop test to determine sponginess or shrink cavities consists in molding a K-shaped casting, breaking the branches of the K and noting the fracture.

760. Hardness of Cast Iron.—From the machinist's point of view no property of cast iron is of more importance than its hardness, since the hardness determines the ease with which the iron can be filed or machined. We have seen that hardness increases with the proportion of combined carbon (Fig. 5) and is much influenced by the proportions of manganese and sulphur; that silicon up to about 3 per cent acts as a softener (Fig. 7) because it promotes the formation of graphite. Therefore, to secure an easily worked iron the proportion of combined carbon must be reduced to the lowest value consistent with requisite strength. In irons where high strength, closeness of grain, and ease of machining are properties much desired, the total carbon is kept low and silicon high.

Additions of chromium, vanadium, or molybdenum promote combined carbon and hardness. Nickel up to 5 per cent graphitizes the iron and promotes machinability, strength, and uniformity.

For determinations of the hardness and depth of chill which will take place in cast-iron castings of different thicknesses, use sometimes is made of a step-bar casting varying from $\frac{1}{8}$ to 1 in. in thickness. After casting the bar against a chill block, it is broken at different steps, the fracture noted, and hardness tests made.

The Brinell hardness test is probably the most satisfactory for most measurements of hardness of gray iron castings. For indications of hardness of small areas, the Rockwell (B-scale) or the Scleroscope are superior. For the harder varieties of white cast irons, the Rockwell (C-scale) or Scleroscope provide satisfactory measures of resistance to indentation.

The Brinell hardness number for gray machinery iron runs from 90 for very soft to 200 for dense strong irons, and from 380 to 500 for ordinary chilled white irons. For the special chilled and heat-treated irons it may reach 700.

761. Influence of Composition and Rate of Cooling on Strength.—For ordinary cast iron it has been noted that the strength is dependent upon the proportion of combined carbon, the proportion and form of the graphite flakes, and upon the closeness and fineness of the grain of the iron. As in steel, the strength of cast iron depends upon the proportion of pearlite. Fineness of grain and of graphite flakes is promoted by cooling as rapidly as is consistent with the attainment of the desired hardness and strength. Further reduction in the size of the graphite particles and improvement in uniformity of dispersion can be had by melting or refining the iron at a high temperature (over 1500° C.) in an electric furnace. These conditions necessitate the use of mixtures low in carbon and sufficiently high in silicon to produce a short solidification period. On the other hand, too much silicon will reduce the combined carbon content of the matrix below eutectoid composition and cause loss in strength.

For making high-strength cast irons a common procedure is to use a low-carbon content, between 2.2 and 3.1 per cent, hold the silicon between 2.2 and 1.2 per cent and the manganese between 1.5 and 0.5 per cent. The carbon content is commonly reduced by additions of steel scrap, thus obtaining a pearlitic matrix with finely divided graphitic flakes.

Of the alloy elements added to cast iron, molybdenum has the most powerful strengthening effect per unit added; nickel and nickel-chromium are also effective in increasing strength.

762. The tensile strength of cast iron is both an important property and a valuable index of the uniformity of cast iron. The tenacity of gray cast iron varies from 20,000 lb./in.^{2}, or less, for soft weak irons to over 60,000 lb./in.^{2} for the high-strength irons for special purposes. The A.S.T.M. standard specifications list seven classes of cast irons based on tensile properties as shown in Table 2. Suitable composition is chosen by the producing foundry unless otherwise stipulated. Roughly, the cost of the cast iron will increase with the strength specified, the high-test irons being much more expensive than the low-strength irons.

Since the tenacity of the iron is much affected by the size of grain and structure, it will decrease as the size of the bar, or thickness of casting, is increased. The effect is more pronounced for the softer, weaker irons, No. 20 and 25, than for the high-strength irons, No. 40 to 60, as the tests in Table 3 show. Such considerations have led to the adoption of three sizes of test bar, each adapted to furnish information for certain thicknesses of castings as indicated in Table 2.

TABLE 2.—A.S.T.M. MINIMUM STRENGTH REQUIREMENTS FOR GRAY IRON CASTINGS

Class.	Required Tensile Strength,* lb./in.²	Minimum Center Breaking Load,† lb. (Optional)			Correlation of Test Bar and Casting.	
		A-Bar, Diam. 0.875 in. Span 12-in.	B-Bar, Diam. 1.2 in. Span 18-in.	C-Bar, Diam. 2.0 in. Span 24-in.	Thickness of Controlling Section of Casting.	Diameter of Test Bar as Cast.
20	20,000	900	1800	6,000	<0.50 in.	0.875
25	25,000	1025	2000	6,800	0.51 to 1.00 in.	1.200
30	30,000	1150	2200	7,600	1.01 to 2.00 in	2.00
35	35,000	1275	2400	8,300	Over 2.00 in.	2.00, or as agreed upon
40	40,000	1400	2600	9,100		
50	50,000	1675	3000	10,300		
60	60,000	1925	3400	. . . .		

* Tests are to be made on threaded end specimens with gaged diameters of 0.505, 0.800, and 1.25 in. for A-, B-, and C-Bar specimens, respectively.

† In transverse tests corrections for deviation in bar diameter, d, may be made by dividing the test load by (d^3/d_n^3), where d_n = nominal diameter.

In making tensile tests it is well to avoid eccentric loading by using threaded-end specimens like Fig. 3*c*, Chap. III, held in sockets provided with spherical seats. Nominal speed of head of testing machine should not exceed ⅛ in. per min. after a load of 15,000 lb. per sq. in. has been imposed on the specimen.

TABLE 3.—PERCENTAGE VARIATION IN STRENGTH OF CAST IRON WITH SIZE OF BAR. (From Symposium on Cast Iron, *Proc. A.S.T.M.*, Vol. 33, Pt. 2, p. 115)

Tests reported by Gray Iron Institute — Tests of Rother and Mazurie

Relative Tensile Strength for Bar Diameters of					Modulus of Rupture of 1-in. Bar as Cast, Span 12-in., lb./in.²	Percentage of Strength of 1-in. Bar for Bar Diameters of			
Class No.	¾-in.	1.1 in.	1.6 in.	2.0 in		1½ in.	2 in.	2½ in.	3 in.
20	100	79	60	53			Soft Iron		
25	100	81	73	72	49,000	96	88	80	76
30	100	78	71	67	53,000	93	84	83	78
35	100	83	68	66	56,800	95	88	86	84
40	100	85	80	67	—	—	—	—	—
50	100	90	79	72	52,900	95	87	83	79
							Machinery Iron		
					69,400	95	96	92	87
					71,000	94	94	84	81
					—	—	—	—	—
					70,200	95	95	88	84

A very comprehensive series of tests on 25 cast irons of different grades was reported by Committee A3 in *Proc. A.S.T.M.*, Vol. 33, Pt. 1, p. 87. Information about these irons is given in Tables 4 and 5.

For these tests twenty 1.4-in. round bars 21 in. long were cast from each of the irons represented in green sand molds in flasks containing 4 bars each. Irons *J* and *V* were

TABLE 4.—CASTING AND COMPOSITION OF CAST IRONS TESTED

(Tests of Committee A 3, *Proc. A.S.T.M.*, Vol. 33, Pt. 1)

Iron.	Furnace.	Temperature °C.		Mix Per Cent			Average Chemical Analysis Per Cent										
		Pouring.	Freezing.	Steel.	Cast Iron.	Pig Iron.	Total Carbon.	Graphite.	Combined Carbon.	Silicon.	Phosphorus.	Manganese.	Sulphur.	Nickel.	Chromium.	Titanium.	Copper.
C	Cupola	1352	1158	10	0	90	3.95	3.09	0.86	1.90	0.07	0.65	0.06	0.01	0.00	0.04	0.32
U	Arc Furnace	1360	1164	12	0	88	3.52	2.68	0.84	2.94	0.04	0.66	0.04	0.01	0.01	0.03	0.34
W	Cupola	1358	1163	37	0	63	3.79	2.99	0.80	1.47	0.12	0.73	0.08	0.01	0.01	0.11	0.21
D	Cupola	1331	1105	13	20	67	3.25	2.66	0.59	2.08	1.99	0.53	0.05	0.03	0.00	0.16	0.02
F	"	1279	1133	10	15	75	3.61	2.93	0.68	2.06	0.75	0.52	0.06	0.00	0.00	0.08	0.02
I	"	1264	1139	0	47	53	3.41	2.85	0.56	2.44	0.63	0.57	0.07	0.01	0.02	0.10	0.03
M	"	1347	1164	25	47	28	3.46	2.82	0.64	2.35	0.15	0.69	0.09	0.65	0.02	0.04	0.03
X	Arc Furnace	1412	1145	0	0	100	3.08	2.32	0.76	2.07	0.04	1.21	0.05	16.3	1.89	0.04	6.12
B	Cupola	1420	1137	12	21	67	3.53	2.69	0.84	1.67	0.68	0.56	0.08	0.00	0.00	0.06	0.06
O	"	1360	1172	13	46	41	3.43	2.75	0.68	2.35	0.20	0.73	0.09	0.01	0.01	0.04	0.03
A	Cupola	1285	1140	10	20	70	3.49	2.72	0.77	1.68	0.74	0.54	0.07	0.00	0.01	0.07	0.10
E	"	1322	1174	4	40	56	3.12	2.44	0.68	2.18	0.63	0.44	0.10	0.00	0.00	0.06	0.02
G	"	1312	1152	20	45	35	3.49	2.78	0.71	2.08	0.19	0.55	0.08	1.17	0.65	0.05	0.02
H	"	1302	1175	10	55	35	3.39	2.75	0.64	2.50	0.43	0.74	0.06	0.01	0.00	0.16	0.04
K	Arc Furnace	1367	1173	20	80	0	3.14	2.30	0.84	2.69	0.18	0.82	0.09	0.25	0.09	0.04	0.06
N	" "	1335	1223	0	0	100	2.53	2.03	0.50	3.26	0.02	1.01	0.04	10.6	1.55	0.05	4.07
S	Cupola	1272	1172	40	0	60	3.38	2.59	0.79	1.18	0.14	0.82	0.08	0.95	0.01	0.05	0.05
R	Air Furnace	1356	1177	0	50	50	3.24	2.41	0.83	1.63	0.42	0.56	0.08	0.06	0.01	0.09	0.04
T	Cupola	1306	1180	0	98	2	3.49	2.16	1.33	0.53	0.33	0.42	0.13	0.00	0.01	0.01	0.05
Y	Rotary Coal	1296	1142	12	38	50	3.07	2.22	0.85	1.97	0.40	0.63	0.07	0.01	0.00	0.04	0.12
*L**	Arc Furnace	1364	1181	20	80	0	3.05	2.20	0.85	2.70	0.16	0.79	0.09	0.60	0.24	0.03	0.02
Q	Rocking Elec.	1351	1172	23	77	0	2.88	2.25	0.63	1.99	0.43	0.51	0.10	0.01	0.01	0.05	0.04
V	Cupola	1334	1218	85	0	15	2.50	1.50	1.00	2.20	0.04	0.74	0.09	0.00	0.08	0.01	0.12
J	Cupola	1322	1214	85	15	0	2.61	1.73	0.88	2.38	0.06	0.77	0.10	1.08	0.09	0.02	0.05
Z	Arc Furnace	1448	1170	68	0	32	2.79	1.94	0.85	2.44	0.03	0.50	0.06	0.50	0.09	0.02	0.36

* Also contained 0.45 per cent Mo.

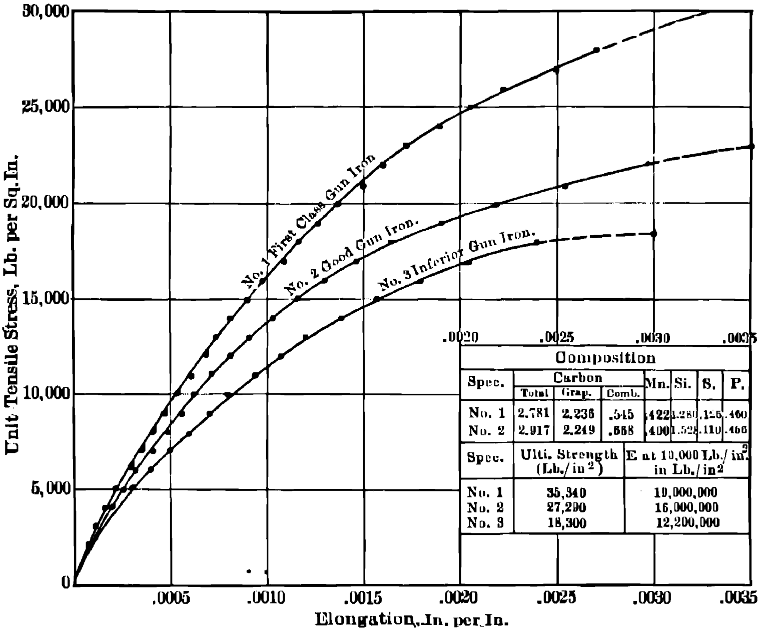
TABLE 5.—AVERAGE MECHANICAL PROPERTIES OF CAST IRONS

(From Report of Committee A 3, *Proc. A.S.T.M.*, Vol. 33, Pt. 1)

Iron.	A.S.T.M. Class.	Tension.		Compressive Strength, lb. in.^{2}, $\times 10^{-3}$.	TRANSVERSE TESTS					Russell Pendulum Impact Tests Energy of Rupture in. lb. in.^{3},		Shear Strength, 0.505-in. Bar, lb., in.^{2},	Endurance Limit, Bar Diam. 0.303-in., lb. in.^{2}	Hardness Halfway from Center of 1.2-in. Bar.	
					On Bar 1.2 in. Diam. 18-in. Span					Span					
		Strength lb. in.^{2}, $\times 10^{-3}$.	Mod. of Elasticity at ¼ Ult. $\times 10^{-6}$, lb. in.^{2}		Mod. of Elasticity at ¼ Ult. $\times 10^{-6}$, lb. in.^{2}	Max. Center Load, lb.	Max. Defl., in.	Modulus of Rupture lb. in.^{2}, $\times 10^{-3}$.	Energy of Rupture in. lb. in.^{3}	18-in.	8-in.			Brinell.	Rockwell B-Scale.
C	<20	18.1	9.1	65.2	10.4	1420	0.352	37.7	15.9	23.2	33.0	28.9	8.8	133	71.5
U	<20	17.7	8.8	72.8	11.1	1651	0.370	43.8	19.1	24.6	37.5	29.6	10.0	146	78.0
W	<20	18.4	9.8	77.9	11.9	1771	0.336	47.0	18.6	25.0	41.6	30.4	8.2	139	74.0
D	20	20.2	12.5	90.9	13.3	1254	0.141	33.3	4.9	7.4	16.7	27.5	12.3	179	89.0
F	20	22.3	12.0	91.0	14.2	1857	0.251	49.2	13.7	21.1	30.7	33.0	11.4	163	84.0
I	20	20.0	11.1	87.2	12.8	1840	0.274	48.8	17.1	20.9	32.0	27.7	9.4	158	78.5
M	20	24.8	13.3	90.8	14.6	2200	0.335	58.3	23.0	33.4	46.5	34.2	12.0	161	84.0
X	20	22.4	12.0	86.0	14.5	1970	0.745	52.2	55.6	54.9	116.5	33.9	10.6	120	68.0
B	25	29.0	12.5	107.2	14.3	2342	0.293	62.2	20.4	24.4	38.2	38.0	14.1	183	88.5
O	25	25.9	13.0	95.0	14.6	2218	0.341	58.7	24.2	30.2	47.9	35.5	11.8	163	82.0
A	30	31.6	13.6	111.0	15.9	2457	0.284	65.1	20.8	27.1	39.0	40.2	14.8	183	89.0
E	30	33.2	16.8	120.8	17.4	2758	0.301	73.2	24.7	31.5	46.0	44.6	16.5	192	90.5
G	30	31.7	12.5	108.8	14.4	2651	0.331	70.3	26.1	28.8	42.4	42.3	13.5	181	86.0
H	30	32.3	14.5	116.1	16.7	2407	0.245	63.9	17.3	22.6	37.5	42.2	18.6	196	90.5
K	30	34.4	15.0	115.9	16.2	2590	0.293	69.7	22.6	31.5	44.5	44.3	16.5	194	93.0
N	30	31.8	9.9	134.2	13.2	2414	0.471	64.4	36.[illegible]	93.5	102.2	43.8	12.8	226	92.0
S	30	32.1	15.0	112.0	17.9	2455	0.267	65.0	19.7	29.5	48.7	41.0	16.0	187	91.5
R	35	37.5	15.7	120.8	17.8	2905	0.326	77.0	28.6	34.7	57.1	47.6	17.4	196	93.0
T	35	35.7	17.8	123.5	19.9	2835	0.294	75.2	26.6	28.8	52.9	47.8	....	207	95.5
Y	35	36.0	15.0	124.5	16.5	2776	0.308	73.5	25.4	27.6	39.6	44.3	16.2	215	94.0
L	40	41.8	16.7	131.2	17.9	3083	0.301	81.8	26.8	39.6	53.9	44.2	18.2	228	96.0
Q	40	41.7	16.7	119.1	19.1	3177	0.439	84.2	46.5	47.2	64.[illegible]	47.3	19.6	190	88.5
V	40	48.1	20.9	159.0	22.6	3472	0.230	92.0	21.9	28.4	43.2	60.8	25.2	266	101.5
J	50	51.0	18.6	156.6	19.1	3489	0.272	92.5	26.8	47.5	56.5	61.0	24.0	269	102.5
Z	50	55.5	18.7	135.7	19.9	4200	0.490	111.7	67.2	80.[illegible]	103.3	57.1	25.0	236	97.0

cast in vertical dry sand molds. All temperatures were carefully measured by the same observers. Bars were machined to a diameter of 1.2 in. prior to testing in impact or bending. Tension and endurance specimens were cut from virgin bars. The tensile strengths reported were obtained from specimens 0.8 in. in diameter but the tensile moduli of elasticity values were obtained from specimens 0.505 in. in diameter. Compression tests were made on cylindrical specimens 1.2 in. in diameter and 4 in. long, loaded through a spherical bearing. Fatigue tests were made on R. R. Moore machines of the rotating beam type. Shear tests were made with a double shear device on cylinders 0.505 in. in diameter. The hardness tests reported were made halfway out on cross-sections of 1.2-in. diameter bars. From two to six Brinell, and three to ten Rockwell, readings were taken on each position. The endurance-test values represent only one test; other test results usually represent the average of three tests. Irons *T* and *X* exhibited some shrinkage cavities at the center of the bars which spoiled small specimens cut from these irons. Iron *T* also showed considerable variations in structure and composition.

The tensile data for these cast irons have been grouped in Table 5 in accordance with the A.S.T.M. classification. The first three irons listed in the table are very weak, whereas the last eight irons belong in the high-strength class.



Composition

Spec.	Carbon			Mn.	Si.	S.	P.
	Total	Grap.	Comb.				
No. 1	2.781	2.236	.545	.422	1.280	.125	.460
No. 2	2.917	2.249	.668	.400	1.528	.110	.466

Spec.	Ulti. Strength (Lb./in^2)	E at 10,000 Lb./in.^{2} in Lb./in^2
No. 1	35,340	19,000,000
No. 2	27,290	16,000,000
No. 3	18,300	12,200,000

FIG. 10.—Stress-diagrams for Gray Cast Iron in Tension. (*Tests of Metals*, 1899.)

White cast iron, such as is used for making malleable cast iron, has a tensile strength commonly varying between 40,000 and 50,000 lb./in.^{2} In small sections the tenacity may reach 60,000 to 70,000 lb./in.^{2}

The endurance limit (see Art. 823) for the cast irons listed in Table 5 varied from 43 to 58 per cent of the tensile strength and averaged 49 per cent of the tensile strength. The characteristics of stress-deformation curves for gray cast iron are shown in Fig. 10. As the curves show, the material has no well-defined proportional limit, but the apparent elastic limit (Art. 11) is approximately 60 per cent of the ultimate strength. The stress-deformation diagram for white cast iron is a straight line. Inasmuch as the maximum unit deformation of most cast iron is less than 0.005, it is impractical to measure it in commercial testing. Hence, in such tension tests of cast iron, no index of ductility or toughness is furnished.

763. The crushing strength of cast iron is remarkably high, and hence this property is considerably utilized in construction. Ordinarily, owing to the high capacity of machine required, tests of the crushing strength are not made. Results in Table 5 indicate that the compressive strength of gray cast iron is 3 to 4 times the tensile strength, the ratio being greatest for low-strength and least for high-strength irons. When tests are made on small prisms with height at least one and one-half times the least lateral dimension, the crushing strength will range from 60,000 lb. per square inch for the soft open-grained gray irons to 200,000 lb. per square inch for the hard close-grained gray irons. (See also Fig. 7.) Machinery gray iron of good quality will have a crushing strength of 100,000 to 140,000 lb. per square inch. White cast iron is one of the strongest metals when subjected to compression, and often has a strength of 250,000 to 275,000 lb. per square inch. As in tensile tests, the position of the test-piece in the casting influences the compressive strength. Pieces cut from near the surface of a casting are stronger than those from the interior. Specimens from small castings are stronger than those from large castings of the same metal. Sometimes variations in strength due to these causes amount to 100 per cent of the smallest values.

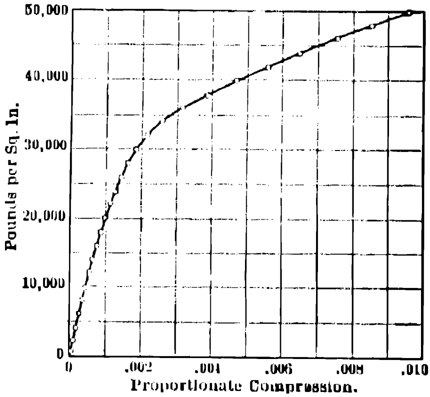


FIG. 11.—Average Results of Twenty-two Compression Tests on Gun Iron. (*Tests of Metals*, 1894.)

The stress-diagram of Fig. 11 is representative of good gray iron in compression, being the average of results from twenty-two tests of gun-iron. The specimens were 10.5 in. long and only 1 sq. in. in cross-section. Consequently they all failed by triple flexure, as columns, at an average stress of 63,000 lb. per square inch before the true crushing strength was reached. (The tensile strength of this iron averaged 33,500 lb. per sq. in.)

In Table 6 are given the results of available tests on full-size cast iron columns. The very low strength of these columns is noteworthy and shows the necessity for testing full-size pieces, rather than small prisms, in order to gauge the strength of large members. The remarkable discrepancy here shown between the crushing strength of small specimens of cast iron and that of full-size members is doubtless due to such hidden defects as shifted cores, blow-holes, and segregation. Nevertheless, such defects are always likely to be present. Furthermore, the results emphasize the importance of carefully calipering cast-iron columns and pipes in order that variations in wall thickness due to shifting of cores may be detected. As the computations in the table indicate, the straight-line formula, $P/A = 34{,}000 - 88\ l/r$, very closely fits the observed results.

764. The Transverse Strength of Cast Iron.—Transverse tests of cast iron have found much favor because the specimens are quickly prepared at low cost; the required testing machine is simple and readily operated by inexperienced men, and the results measure strength, flexibility, and toughness. Hence this test is much more informative than the tensile test, though the latter is the specification requirement. Tests are now made on the three sizes of round bars shown in Table 2. Bar lengths are 3 in. longer than the indicated test span. Diameter of bar should always be carefully measured prior to testing. Strength is indicated by the center load which the specified bar will carry. A rough measure of toughness may be found by estimating the energy of rupture from half of the product of the maximum load times the corresponding deflection.

The modulus of rupture of cast iron is not usually computed in the foundry, but it forms the best means of comparing bars of the same shape which differ slightly in size. Comparisons cannot well be made between bars differing considerably in size or in shape, since the rate of cooling causes radical changes in the grain structure of the interior. Variations in the moduli of rupture of square bars due to differences in area and in silicon content are shown in Fig. 9. Square bars, in general, exhibit a modulus of rupture 10 to 18 per cent lower than round bars of equal diameter. Variations in the modulus of rupture due to differences in shape of cross-sections are illustrated in Table 1, Chapter III. Machined bars are generally weaker than unmachined specimens. Tumbling in a rattler materially improves the strength and increases the hardness of the skin. Bars cast horizontally are strongest when the load is applied against the cope face.

The ratio of the modulus of rupture (S_m) to the tensile strength (S_t) varies from 1½ to 2½ (see Art. 27). The ratio, S_m/S_t, decreases as the tensile strength increases. This relation is discernible in values given in Table 5.

TABLE 6.—TESTS OF FULL-SIZE CAST-IRON COLUMNS

(Results of Tests made at Phœnixville, Pa., by New York Department of Buildings, 1897)

Number of Column.	Diameter. Inches.	Thickness of Metal, Inches.	Area in Square Inches.	Length in Inches. (l).	Actual Breaking Load per Square Inch in Pounds.	Radius of Gyration (r)	$\frac{l}{r}$	Breaking Load by Formula $p=34000-88\frac{l}{r}$
I	15	1	43.98	$190\frac{1}{4}$	30,830	4.962	38.341	30,630
II	15	$1\frac{1}{8}$	49.03	$190\frac{1}{4}$	27,126	4.92	38.668	30,600
B2	15	$1\frac{1}{8}$	49.03	$190\frac{1}{4}$	24,434	4.92	38.668	30,600
B4	$15\frac{1}{8}$	$1\frac{1}{8}$	49.48	$190\frac{1}{4}$	25,182	4.965	38.318	30,630
(5)	15	$1\frac{11}{64}$	50.91	$190\frac{1}{4}$	35,435*	4.936	38.543	30,610
(6)	15	$1\frac{3}{16}$	51.52	$190\frac{1}{4}$	40,411	4.899	38.834	30,580
XVI	8	1	21.99	160	29,604	2.50	64.00	28,370
XVII	8	$1\frac{3}{64}$	22.87	160	28,229	2.486	64.361	28,340
(7)	$6\frac{1}{16}$	$1\frac{9}{64}$	17.64	120	25,805	1.786	67.189	28,090
(8)	$6\frac{3}{32}$	$1\frac{7}{64}$	17.37	120	26,205	1.805	66.483	28,150
G4	8	$\frac{3}{4}$	17.083	$147\frac{3}{4}$	25,969	2.741	53.903	29,260
F4	9	1	25.133	150	21,181	2.872	52.226	29,410
D4	12	1	34.588	162	30,810	3.906	41.475	30,350
C2	14	1	40.841	$159\frac{3}{4}$	25,401	4.609	34.661	30,950

* Did not fail.

RESULTS OF THE WATERTOWN ARSENAL TESTS

(*Reports* for 1887 and 1888)

Number of Column.	Least Diameter in Inches.	Approximate Thickness of Metal in Inches.	Least Area in Square Inches.	Length in Inches. (l)	Actual Breaking Load per Square Inch in Pounds.	Radius of Gyration (r).	$\frac{l}{r}$	Breaking Load by Formula $p=34000-88\frac{l}{r}$
990	5.94	0.98	13.19	131.6	38,860	2.11	62	28,540
991	5.90	0.95	12.27	146.7	43,350	2.12	69	27,930
992	5.09	0.85	12.08	150.0	33,500	1.77	85	26,520
993	4.74	0.91	11.75	151.5	26,840	1.61	94	25,730
994	4.84	0.91	11.89	128.6	30,370	1.63	79	27,050
995	4.87	0.90	11.80	129.5	29,830	1.64	79	27,050
996	5.72	0.66	8.94	127.6	63,310	2.12	60	28,720
997	2.97	0.87	5.19	118.5	31,850	.97	122	23,270
998	3.00	0.88	5.27	118.7	29,990	.97	122	23,270
999	3.00	0.90	5.50	118.4	33,350	.97	123	23,180
1000	4.27	1.00	10.92	84.6	32,130	1.31	65	28,280
2000	8.66	1.36	31.10	157.0	(25,720)*	2.63	60	28,726
2001	7.87	1.31	26.33	156.9	(30,380)*	2.37	66	28,160
2002	7.17	1.16	21.75	156.9	25,470	2.16	73	27,540
2003	6.35	1.13	17.28	156.9	27,210	1.89	83	26,650
2004	5.57	0.77	13.22	156.4	25,100	1.71	97	25,360

* Did not fail.

The modulus of rupture varies with the span as shown in Fig. 15, Ch. III. MacKenzie and Donoho reported additional data for strips of pipe-iron which they tested (see *Proc. A.S.T.M.*, Vol. 37, Pt. 2, p. 71).

Average values for the modulus of rupture of good grades of cast iron may be expected to be not less than the following: No. 20, 48,000 lb./in.^{2}; No. 25, 53,000 lb./in.^{2}; No. 30, 58,000 lb./in.^{2}; No. 35, 64,000 lb./in.^{2}; No. 40, 69,000 lb./in.^{2}; No. 50, 80,000 lb./in.^{2}; and No. 60, 90,000 lb./in.^{2}.

Good grades of gray cast iron usually deflect between 0.1 to 0.2 in. when tested in A-bars (Table 2), 0.2 to 0.4 when tested in B-bars, and 0.2 to 0.3 when tested in C-bars.

The energy of rupture in bending, accurately found by evaluating the area under the load-deflection curve and dividing by the volume of the specimen, serves to measure the toughness or resistance to shock of the iron. Where the complete load-deflection data are not obtained, the total energy consumed may be roughly approximated by taking half the product of the maximum load times the corresponding deflection.

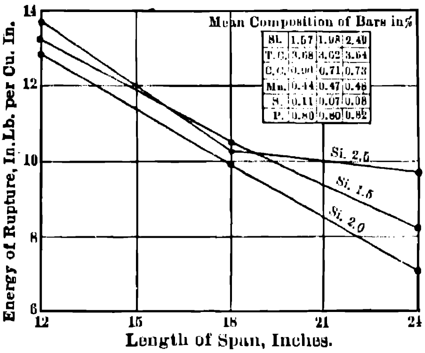


FIG. 12.—Influence of Length of Span on the Energy of Rupture of 1¼-in. Round Bars of Cast Iron. (Mathews.)

Owing to the limited portion of the specimen suffering maximum stress, the energy of rupture decreases markedly with the length of the span, as the data in Fig. 12 show. Also thick specimens usually show lower energies per unit volume than thin ones. Hence comparisons should be based on standard conditions.

In Fig. 13 are shown autographic stress-diagrams of four kinds of cast iron. The tests were made on bars ½ in. square and 12 in. long. They all withstood a load of 450 lb. at the center, which gives a modulus of rupture of 64,800 lb. per square inch. Owing to the great differences in ultimate deflection, however, their resistances to shock vary greatly. By computing the areas under the load-deflection curves and dividing by the volume of the test-piece between supports, we find their resistances are 10.0, 21.5, 28.9 and 35.1 in. lb. per cubic inch. For these four cases, the greatest error, due to approximating the energy of rupture by the method previously outlined, would be 16 per cent.

Good gray irons exhibit energies of rupture of 18 to 30 in. lb./cu. in. when tested in either A-bars or B-bars. Phosphorus in high percentages causes a lack of toughness as evidenced by data for the *D*-iron, Table 5.

In contrast the high toughness of the low-carbon and high-nickel irons of Table 5 is noteworthy.

765. The modulus of elasticity of cast iron varies considerably with the strength of the iron, as the data in Fig. 7 and Table 5 show. If the secant modulus (Art. 519) is determined for maximum stresses of one-fourth of the ultimate strength, the value for good grades of machinery iron usually lies between 13,000,000 and 16,000,000 lb./in.^{2} with values of 20,000,000 lb./in.^{2}, or higher, for high-test irons. For white cast iron, E lies between 25,000,000 and 30,000,000 lb./in.^{2} The data from the A.S.T.M. Impact Investigation indicated that the moduli in tension and compression were approximately equal but averaged about 11 per cent less than the values calculated from transverse bending tests. The latter discrepancy is undoubtedly due to the presence of stronger and stiffer metal in the outside portions of the specimens tested. Hence for the same quality of cast iron the modulus of elasticity is the same in tension, compression, and bending. The shear modulus of elasticity (E_s) is 0.4 E.

766. Shock Resistance of Cast Iron.—In cast-iron car wheels, in rolls and jaw plates for crushers, in grinding balls, and in forming dies considerable shock must often be sustained. Hence the energy of rupture in cross bending or impact is sometimes a decidedly important property. The energy of rupture in transverse impact is usually 20 to 35 per cent higher than the energy of rupture found in static bending. Good machinery irons will usually show 25 to 35 in.-lb./cu. in. when tested in B-bar specimens. On an 8-in. span the energy per unit volume for 1.2-in. diameter specimens is 50 to 70 per cent higher than for an 18-in. span (Table 5). When tested in $\frac{3}{4}$-in. bars over an 8-in. span, good iron of No. 30 grade will exhibit energy of rupture values of 28 to 35 in.-lb./in.^{3}.

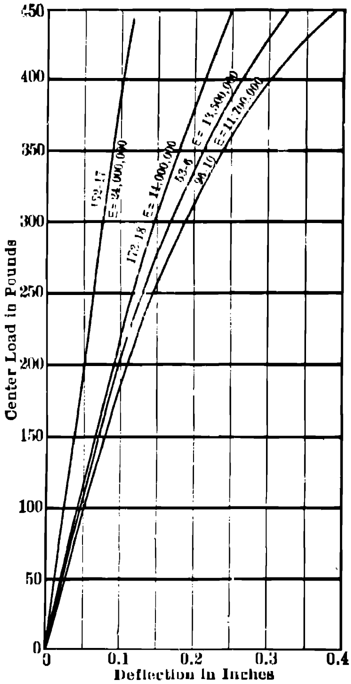


FIG. 13.—Cross-bending Autographic Stress Diagrams of Four Kinds of Cast Iron all of Equal Strength. (Keep, *Trans. A. S. M. E.*, Vol. 17, p. 677.)

767. Strength of Cast Iron in Shear and Torsion.—The shear strength of cast iron, determined by double shear tests on small cylindrical or thin rectangular specimens, provides a good method for exploring the uniformity of the strength of a casting. For such purposes cylindrical specimens may be cut from the casting by a core drill (see Fremont's report in *Proc. I.A.T.M.*, the VI Congress, VI₄.).

The shear strength of gray cast iron usually is between 25,000 and 60,000 lb./in.². The property increases with the tensile strength but in a decreasing ratio. For No. 20 cast iron the shear strength is about 1.6 times the tensile strength, whereas for No. 35 the ratio approximates 1.3, and for No. 60 the ratio is about 1.0.

In torsion, cast iron fails on planes at 45 deg. with the torsional shear stresses. Since these failure planes carry tensile stresses of intensities equal to the shears, it is evident that such failures are caused by weakness in tension.* Round bars of No. 30 cast iron should exhibit computed twisting strengths (S_s') between 40,000 and 50,000 lb./in.².

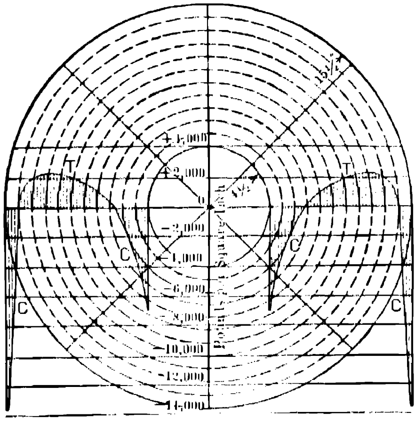


FIG. 14.—Shrinkage Stresses in Cast Iron Cannon 11 in. thick. (*Tests of Metals.*)

768. Shrinkage Stresses.—The shrinkage of cast iron in cooling often induces excessive stresses, sometimes sufficient to rupture. Such stresses increase with the thickness of the casting. An example of an analysis of shrinkage stresses in a heavy cannon is shown in Fig. 14. The outer and inner surfaces cooled first, and the subsequent shrinkage of the interior put these parts in compression. But since the total internal stress across any diametral section must be zero, there being no external force acting, it follows that the total tensile stress must equal the total compressive stress. The stresses were all found directly by cutting off a zone included between two transverse sections, and by cutting this into a series of concentric rings as shown by the dashed lines in Fig. 14. Before cutting these, four diameters of each ring were carefully measured, and these same diameters were again measured after cutting out. An increase in mean diameter indicated an initial compression, and *vice versa*. The initial stresses were found from the equation $S = \epsilon E$, where S = unit stress in lb. per sq. in.; ϵ = proportionate change in circumference; E = modulus of elasticity.

The stress diagrams of Fig. 14 were drawn from the original data by J. B. Johnson. They show that in this simple symmetrical casting there were compressive stresses on the inner and outer surfaces of 7,000 and

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* Verified by tests on thin hollow cylinders of cast iron reported by J. O. Draffin and W. L. Collins, *Proc. A.S.T.M.*, Vol. 38, Pt. 2, p. 235.

13,500 lb./in.^{2}, respectively, and tensile stresses of 2,000 lb./in.^{2} in the interior portions. In more complex forms of castings the determination of such stresses would be far more difficult, but their magnitudes might be much greater.

769. Strength of Cast Iron Increased by Shocks.—Rattling of castings or imposition of a large number of light blows is likely to produce an increase of 10 to 15 per cent in strength and 20 per cent increase in impact toughness, according to A. E. Outerbridge, *Trans. Am. Inst. Min. Engr.*, Vol. 26, p. 176. This action appears to be due to relief of internal strain and a densification and hardening of the surface where the castings are tumbled in the rattler.

770. Heat Treatment of Cast Iron.—Cast iron responds to heat treatment in a manner similar to steel. Internal strains may be relieved by annealing at 430 to 490° C. for ½ to 4 hr., in accordance with the mass and thickness of the casting, and cooling slowly. Such treatment slightly decreases hardness and strength properties but materially improves toughness and constancy of shape after machining. The softer, low-strength irons of high graphite content will be weakened more than the high-strength irons of low graphite content by such treatment. Raising the temperature or increasing the annealing period will cause further reductions in hardness and tenacity. Softening of hard castings for purposes of machining can be done by annealing at temperatures of 760 to 820° C.

Wear and abrasive resistance of cast irons carrying fine-grained, uniformly dispersed graphite in a pearlitic matrix can be improved by skillful quenching from above the critical range, 790–850° C. If desired, the drastic hardening effects of quenching may be relieved and the tenacity improved by drawing at temperatures of 300–400° C.

Surface hardness of 800 to 950 Brinell can be produced on finished castings by subjecting irons of low-carbon content containing aluminum and chromium to the nitriding process (see Art. 710).

771. Effect of Repeated Heating on Cast Iron.—Repeated heating of high-carbon, gray cast irons at temperatures above 500° C. gradually causes a break down of the pearlite into ferrite plus graphite, with accompanying increase in volume or growth. At 725° C. allotropic transformations intensify these growth changes. Furthermore, in connection with such heating, there is likely to be corrosive action which by its nature accentuates growth. Indeed the action of superheated steam, if corrosive, may effect undesirable growth in gray iron fittings at temperatures below 500° C.

Cast irons of low total carbon, with finely divided, uniformly dispersed graphite flakes and well-stabilized carbide, are the most resistant of the ordinary cast irons. The inclusion of chromium and other ingredients tending to promote stability of iron carbide at high temperatures make the cast iron more resistant to growth from repeated heating. In ordinary amounts silicon promotes graphitization and growth but irons with 6.1 per cent of silicon have shown little growth (see Symposium on Cast Iron, *Proc. A.S.T.M.*, Vol. 33, Pt. 2, p. 115).

MALLEABLE CAST IRON

NATURE AND IMPORTANCE

772. Nature.—White cast iron of suitable composition can be rendered somewhat malleable and ductile, and very greatly toughened by surrounding it with a suitable packing material and annealing at a bright red heat for several days. The iron before annealing should have all of its carbon in combined form, but the silicon, sulphur, and manganese contents must be so adjusted that the annealing may be accomplished at temperatures just above the critical range (1300 to 1500° F.). By the heat treatment the combined carbon is transformed into a special type of graphitic carbon, called *temper* carbon. The temper carbon is made up of finer, more-rounded, and more-uniformly disseminated grains than the graphite of gray cast iron.

If the packing material is loose and the furnace gases strongly oxidizing, practically all of the carbon will be removed from the outer layer of iron, the percentage removed decreasing toward the center of the casting. In American practice the entire annealing period is only six or seven days and the carbon removal is small. Examination of a fractured cross-section of malleable cast iron reveals a thin white shell of impure carbonless iron about $\frac{1}{64}$ to $\frac{1}{32}$ in. thick surrounding a black core in which the grains of temper carbon are imprisoned among crystals of iron (ferrite). The color of the core in the fractured casting gives rise to the name *black heart*. In Europe the annealing process is carried on at a higher temperature and for a considerably longer time. This results in the production of a much thicker shell of decarburized iron, and a greater reduction in total carbon than in American practice. The castings so produced have a *white heart*, and are coarser grained and somewhat less strong than black-heart castings. By providing chills in molding the white iron it is possible to make castings up to 4 in. in thickness by the black-heart process. The white-heart process is best adapted to production of parts under $\frac{1}{2}$ in. in thickness.

In strength, malleable cast iron is considerably superior to gray cast iron but inferior to steel castings. It is very much tougher than gray iron and, when well made, compares favorably with cast steel. Owing to lower melting temperature white cast iron shrinks slightly less than steel and in the annealing process an expansion takes place, due to the separation of the temper carbon, which makes the net shrinkage of malleable cast iron about the same as gray cast iron. Malleable castings are in general somewhat smoother and freer from blow-holes than steel castings, and also more resistant to corrosion.

773. Importance of Malleable Cast Iron.—On account of good strength, high toughness, and moderate cost, malleable cast iron is much used for a large variety of small castings. About one-half of the 600,000 tons of malleable cast iron annually produced in the United States is used by railroads on rolling stock for car couplers, journal boxes, brake wheels, levers, door fasteners, hinges, pipe hangers, etc. A large tonnage is used in making parts of agricultural machinery and implements, while most of the remainder is used for pipe fittings, stove plate, hardware, ornamental castings and cheap tools. About one hundred and fifty foundries in the United States produce more malleable cast iron than is made in all the rest of the world.

THE MANUFACTURE OF MALLEABLE CAST IRON

774. Melting the Charge.—The cupola, the air-furnace and the open-hearth furnace are the types of furnaces most used for melting the charge. Baby Bessemer converters and crucibles are used to some extent in Europe and the electric furnace is also forcing its way into this field.

The principal use of the cupola in malleable iron works is for making small castings. The process is run in much the same way as in smelting gray cast iron excepting that a larger proportion of fuel is required in order that the white iron, which is less fluid than gray, may be very hot when poured. The composition of pig iron for such castings according to Moldenke should be about as follows: Silicon 1.00 to 1.50, manganese <0.60, phosphorus <0.225 and sulphur <0.05 per cent. Small amounts of pig iron and sprues are charged between thin layers of coke or anthracite coal. Malleable or steel scrap cannot be advantageously used in this type of furnace. Iron is run continuously from the tap hole into ladles and poured as rapidly as possible. The cupola is the cheapest in installation, in upkeep and in operation, and the quickest smelting process in general use. However, owing to contact between the fuel and the iron and lack of means of control, burnt metal is sometimes produced. Furthermore, the annealing temperature required for cupola iron is higher than for the air-furnace or open-hearth product.

The air-furnace is used most in this country for making malleable castings. It is less expensive to install and operate than the open-hearth, although requiring a slightly longer time for smelting. It may be built in a wide variety of sizes, and can be operated discontinuously without impairing the quality of the iron. One of the main difficulties in air-furnace operation is the possibility of burning the thin portions of the bath and consequent production of weak metal. By proper use of the air-furnace it is possible to produce a very good grade of malleable iron with less skill than required to run an open-hearth furnace. The charge of metal for the air-furnace consists of pig iron, white-iron scrap, and malleable scrap. When necessary to reduce carbon to proper limits (2.25 to 3.00 per cent) a small proportion of steel or wrought iron scrap is added after the pig iron has melted. For heavy castings the silicon content in the pig iron is run lower than indicated for cupola iron in order to avoid mottling of the hard iron castings. Fig. 6 indicates ranges in carbon and silicon contents in hard iron for making different grades of malleable cast iron.

The open-hearth furnace for malleable iron is built upon the same principle as that used in steel making, but in smaller sizes. With the open-hearth furnace the charge of metal is similar to that used in the air furnace. The fuel, however, is usually producer gas and air, both of which are separately heated by passage through hot checker works before they enter the furnace. Natural gas and vaporized fuel oil are sometimes used instead of producer gas. Although the most costly process on account of high cost of installation, upkeep and skilled labor for operation, the open-hearth furnace provides well-controlled melting conditions and furnishes the best malleable cast iron.

775. Molding and Casting.—Because of the lack of fluidity in white cast iron and the rapidity with which it chills, patterns must be provided with large runners and sprues. This should be done in order that the metal may be rapidly poured, also in order that a good head of metal may be provided to keep the mold full during solidification. Owing to the high shrinkage of white cast iron especial care should be taken in shaping patterns at the junctions of thick and thin parts. Suitable chills are often required to cool heavy sections with sufficient rapidity to make the iron white and to avoid excessive shrinkage strains at junctions with thin parts.

The molds used for malleable cast iron are similar to those made for gray castings but, owing to the number of castings made from the same pattern, there is a better opportunity for the effective use of molding machines and core-making machines. Metal molds, on account of the chilling action which they exert, are also successfully used for malleable castings.

In casting, it is quite necessary that the white iron be poured at a temperature sufficiently high to render it fluid; yet, on account of danger of burning, the metal cannot be held too long in the furnace. The narrow range of pouring temperature makes it necessary, therefore, to have the metal handled and cast very promptly when it has arrived at a white heat.

After the white castings have cooled they are shaken out of the sand and cleaned by the methods used for gray castings. They are then trimmed of sprues, ground smooth, where necessary, and sorted.

776. The annealing of the white castings is an exceedingly important operation in the production of good malleable castings. The hard castings are carefully packed in rectangular boxes, called saggars, which are 16 by 24 inches in plan and a foot high. Mill scale from wrought-iron squeezers and silicious slag are often mixed to form the packing material. Hematite and pulverized magnetic ore are also used for this purpose. Leasman and Storey's * experiments show that the oxidizing character of the packing material exercises no influence upon the decarburization of the iron, but that such change is due to the penetration of carbon dioxide generated in the furnace. The permeability of the packing to this gas is therefore the important factor in determining the carbon content in the skin of the castings.

The saggars are stacked 4 deep in an annealing furnace, which, in form and in principle of operation resembles a rectangular down-draft brick kiln. Gas, coal or oil is used to slowly heat the annealing furnace until the temperature of the castings is above the critical range. Storey states the latter is between 700 and 775° C. The temperature is held just above this range from sixty to seventy-two hours and then the castings should be cooled very slowly until well below the critical temperature. For black-heart castings about six days are required for annealing.

After removal from the saggars, the malleable castings are placed in a rattler, which is partly filled with bits of discarded malleable castings, and cleaned. They are then given whatever finishing is necessary. If crooked they are straightened but without heating.

CONSTITUTION AND PROPERTIES OF MALLEABLE CAST IRON

777. Composition and Constitution.—Good black-heart malleable castings will generally contain about 2.0 to 2.8 per cent of temper carbon, 0.50 to 1.25 per cent of silicon, manganese under 0.30 per cent, sulphur below 0.05 per cent, and phosphorus under 0.25 per cent. The higher percentages of silicon are in most cases to be found only in small castings. For intricate patterns where fluidity of the molten metal is of great importance phosphorus may run to 0.3 per cent.

If the annealing is properly done no combined carbon will be found and the entire structure will consist of two main elements, ferrite and temper carbon, as shown in Fig. 15*a*. Such castings should possess maximum

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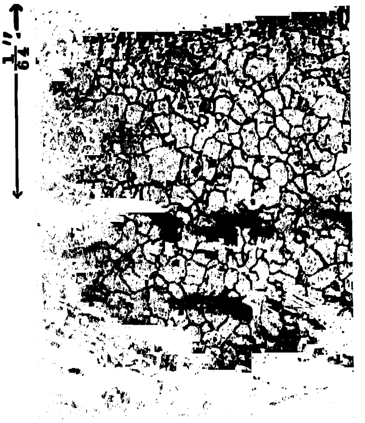
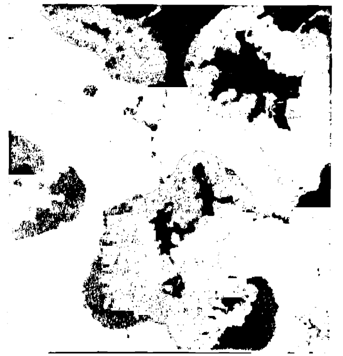
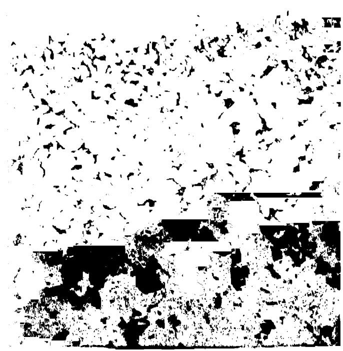
* See account of experiments at University of Wisconsin in *Foundry*, Vol. 42, p. 474.



(a) Good Malleable Iron. Note ferrite shell (top) free from temper carbon which appears as black patches farther in from the surface. (Harbison Walker Refr. Co.)



(b) Temper carbon in ferrite masses which are in turn surrounded by pearlite. (Storey.)



(c) Steely shell (top) caused by close compacting of packing material and lack of oxidation.

Fig. 15.—Photomicrographs of Good and Bad Malleable Iron (×70).

ductility. If the annealing period is too short or the temperature too low, cementite will be present in addition to ferrite and temper carbon and the castings will be more brittle, although they may be stronger than the fully annealed iron. When the castings are cooled too rapidly after correct annealing, the structure shows the temper carbon embedded in ferrite which is in turn surrounded by pearlite, Fig. 15*b*. With too low annealing temperature followed by rapid cooling the structure consists of cementite particles embedded in pearlite masses with more or less temper carbon imprisoned in ferrite. Such iron is likely to be very brittle and non-uniform.

In order to determine whether the iron is of proper constitution a small rectangular lug is cast on the work. After annealing the lug is broken off with a hammer, the toughness of the iron judged by the energy required to remove the lug, and the fracture examined. Good black-heart iron will show a very thin white skin from $\frac{1}{64}$ to $\frac{1}{32}$ in. in thickness surrounding a bluish black or black core. The core should present a velvety appearance and be free from shrink cavities or white crystals.

A recent development in high-strength malleable cast iron has been the production of the *pearlitic malleable cast irons.* These irons are made by incompletely graphitizing the combined carbon of the original white cast iron, or by reheating the graphitized metal. Elements like manganese, chromium, or molybdenum are sometimes added to effect retardation graphitization. Although termed pearlitic, different classes of these metals are made with matrices containing any one of the metallographic constituents common in hardened or tempered steel, (see Fig. 15*b*). Successful production of pearlitic malleable cast iron requires very careful control of composition and heat treatment. Tensile strengths range from 60,000 to 100,000 lb./in.^{2}, the ductilities are lower than for the black-heart malleables, but the toughnesses may be either higher or lower. The pearlitic malleables are harder, less easy to machine, and shrink less than ordinary malleable cast iron. (See also *A.S.T.M. Symposium*, 1936.)

778. Testing of Malleable Cast Iron.—In the foundry, the breaking of hard castings to determine whether the iron is mottled or white and the lug test of the malleablized iron are the principal mechanical tests. It is customary with more important work to run tensile tests on bars shaped about like Fig. 3*f*, Chapter III, with a minimum diameter of $\frac{5}{8}$ in.

A simple test for toughness and ductility, which seems to have found some favor in the foundry, is the curling test. This test is made on a wedge 6 in. long, 1 in. wide, and tapering from $\frac{1}{2}$ in. to $\frac{1}{16}$ in. in thickness, which has been cast and annealed with the given heat. The thin edge of the wedge is bent over with a hand hammer. It is then gripped rigidly at the thick end and held thin edge up under a drop hammer. The hammer is dropped on the specimen from a constant height giving blows of 70 ft.-lb. each. These cause the specimen to curl into a spiral. Lack of ductility is signified by cracking of the wedge, toughness by the number of blows required to break it.*

779. Mechanical Properties of Malleable Cast Iron.—The A.S.T.M. Symposium on Malleable Iron Castings of 1931 furnishes data on the mechanical properties of irons of the following chemical composition: carbon, 1.00 to 2.00; silicon, 0.60 to 1.10; manganese, under 0.30; phosphorus, under 0.20; and sulphur, 0.06 to 0.15 per cent. For such iron the specific gravity was found to vary from 7.15 to 7.45, depending upon the carbon content. The coefficient of thermal expansion up to 400° C. (750° F.) was 0.000012 per deg. C., or 0.0000066 per deg. F. From 20,000 tensile tests, nearly all of which were made on air furnace iron, the average ultimate strength was 54,040, with a range from 45,000 to 62,860 lb./in.^{2} The yield point, based on an elongation of 1 per cent, varied from 30,000 to 43,000 and averaged 36,350 lb./in.^{2} The elongation varied from 8 to 33 and averaged 18.4 per cent. From a statistical analysis of 5,000 tests, representing random heats of many manufacturers, it appears probable that 96 per cent of the tensile strengths were within 4,000 lb./in.^{2} of the average and 60 per cent of the ductility values were within the range 18.4 ± 3 per cent. The average tensile properties reported from 1210 tests on open-hearth furnace iron were ultimate strength 57,920 lb./in.^{2}; yield point, 38,230 lb./in.^{2}, and per cent elongation, 25.7 per cent. Cupola iron, use of which is limited principally to making pipe fittings, is more variable in properties. Tensile strengths reported by 3 manufacturers ranged from 35,000 to 58,200 and averaged 45,200 lb./in.^{2}; and the elongation in 2 inches varied from 2 to 16 per cent and averaged 7.2 per cent.

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* Described by E. Touceda in *Foundry*, Vol. 43, p. 13.

Malleable cast iron is unique in that the elongation increases with the tensile strength. Figure 16 shows relations reported in the symposium and represents several thousand tests. The relations apply only to iron without combined carbon. The A.S.T.M. Standards recognize two grades of malleable cast iron: No. 32510 with a minimum tensile strength of 50,000 lb./in.^{2}, yield point of 32,500 lb./in.^{2}, and elongation in 2 in. of 10 per cent; and No. 35018 with a minimum tensile strength of 53,000 lb./in.^{2}, yield point of 35,000 lb./in.^{2}, and elongation in 2 in. of 18 per cent.

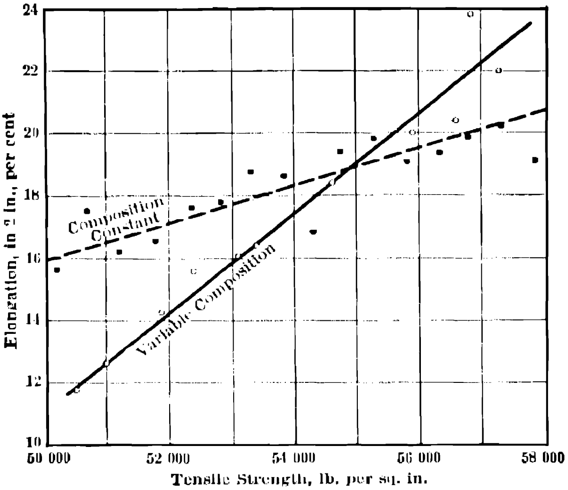

FIG. 16.—Relation of Tensile Strength and Elongation of Malleable Cast Irons (*A.S.T.M. Symposium*, 1931).

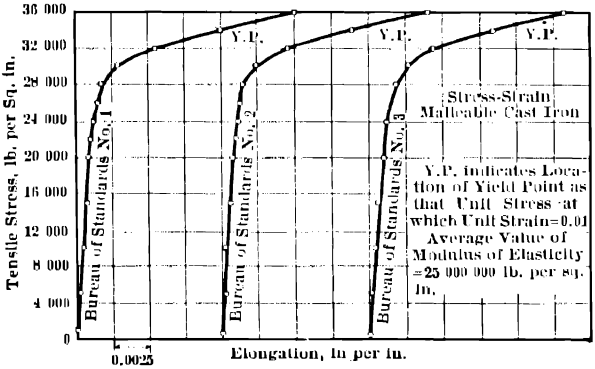

FIG. 17.—Stress-strain Curves for Malleable Cast Iron in Tension (from *A.S.T.M. Symposium* of 1931).

Figure 17 shows stress-strain curves reported in the symposium for these malleable cast irons. Average values of the modulus of elasticity in tension reported by six investigators ranged from 24,000,000 to 27,900,000 lb./in.^{2} and averaged 25,070,000 lb./in.^{2} The modulus of elasticity in compression is approximately the same as in tension; in bending, values usually run from 22,000,000 to 24,000,000 lb./in.^{2}

In compression malleable cast iron takes a permanent set of 1 per cent in the vicinity of 28,000 lb./in.^{2}

In cross bending the extreme fiber stress at maximum load computed from the flexure formula $S = Mc/I$ approximates twice the tensile strength of malleable cast iron when tested in solid square or cylindrical sections. For $\frac{3}{4}$-in. cylindrical specimens tested on a 12-in. span, the modulus of rupture is usually 85,000 to 100,000 lb./in.^{2} and work to maximum load is generally above 350 in.-lb. per cu. in.

The shear strength approximates 48,000 lb./in.^{2} and the shear modulus of elasticity may be taken at 10,000,000 lb./in.^{2} The modulus of rupture in torsion based on 5 tests averaged 58,000 lb./in.^{2} and the yield point 24,850 lb./in.^{2}

Brinell hardness of malleable cast iron usually lies between 100 and 140, averaging about 115.

In the wedge or curling test for toughness and ductility good malleable cast iron will withstand 25 to 30 blows prior to fracture.

In fatigue the endurance limit has not been thoroughly investigated but available data indicate that it is 0.4 to 0.5 of the tensile strength.

Removal of the skin from black-heart malleable cast iron produces little effect on the tensile strength and yield point as indicated by the data of Table 7. The data in the table do demonstrate that the skin is more ductile than the core metal. Other tests were reported by H. A. Swartz in *Proc. A.S.T.M.*, Vol. 20, Pt. 2, p. 70, in which specimens ground before annealing were tested and compared with specimens which had the skin removed to a depth of $\frac{1}{16}$ in. These showed that the tensile strength was reduced about 7,000 lb./in.^{2} and the elongation in 2 in. was reduced about 3 per cent for specimens $\frac{1}{4}$ in. in diameter, whereas the effects on these properties became less as the diameter of the test specimen increased and was negligible for specimens $1\frac{1}{4}$ in. or over in diameter.

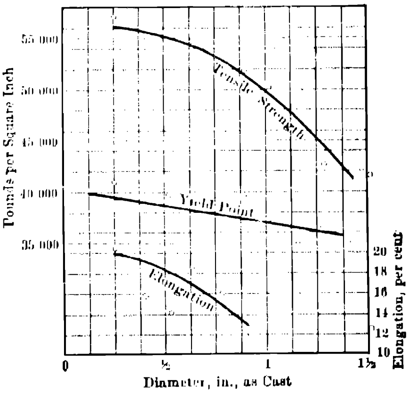

Fig. 18.—Tensile Properties of Malleable Cast Iron Specimens not Machined (H. A. Swartz).

There is an appreciable effect on strength and ductility due to diameter of the specimen as shown in Fig. 18, which is also taken from the tests by Swartz and reported in the *A.S.T.M. Symposium*, 1931.

TABLE 7.—TESTS OF MALLEABLE IRON TEST BARS IN "AS CAST" CONDITION AND MACHINED. (From *A.S.T.M. Symposium*, 1931.)

Iron made by Frazer and Jones Co. in 1920; tests made by Robert W. Hunt Co.

Set	Diameter of Bar as Cast, in.	How Tested	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
No. 1.....	$\frac{5}{8}$	As cast	55,720	35,410	29.0	30.8
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	55,380	35,350	22.5	22.6
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	54,980	34,950	21.5	21.7
	1	Machined to $\frac{5}{8}$ in.	55,140	35,800	19.5	16.9
No. 2.....	$\frac{5}{8}$	As cast	55,880	35,040	25.0	26.2
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	54,840	35,310	20.5	19.7
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	53,740	34,980	15.5	14.2
	1	Machined to $\frac{5}{8}$ in.	53,600	34,500	14.5	13.0
No. 3.....	$\frac{5}{8}$	As cast	56,580	34,600	26.0	30.8
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	55,580	35,760	24.0	24.0
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	55,460	36,320	24.0	20.5
	1	Machined to $\frac{5}{8}$ in.	54,820	35,370	24.0	22.1
No. 4.....	$\frac{5}{8}$	As cast	55,440	35,220	26.0	29.4
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	55,260	35,960	23.0	24.3
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	54,420	35,310	20.0	21.1
	1	Machined to $\frac{5}{8}$ in.	54,540	35,140	23.0	22.6
No. 5.....	$\frac{5}{8}$	As cast	55,200	35,310	26.5	20.8
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	55,380	35,340	22.5	23.5
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	55,020	35,340	21.5	19.2
	1	Machined to $\frac{5}{8}$ in.	53,840	35,370	24.5	22.9
No. 6.....	$\frac{5}{8}$	As cast	55,120	33,720	26.0	29.2
	$\frac{3}{4}$	Machined to $\frac{5}{8}$ in.	54,840	35,120	26.0	25.1
	$\frac{7}{8}$	Machined to $\frac{5}{8}$ in.	55,240	34,310	23.0	23.2
	1	Machined to $\frac{5}{8}$ in.	54,920	34,650	24.0	22.6

For several years the students in the Materials Testing Laboratory at the University of Wisconsin have broken $\frac{3}{4}$-in. round bars of air-furnace malleable cast iron over an 8-in. span in a Russell impact machine (pendulum type). The majority of these specimens had energies of rupture in impact in excess of 1000 in.-lb. per cubic inch and quite a number have withstood 2000 in.-lb. per cubic inch without rupture.

The malleability and toughness of malleable cast iron made in Germany are well illustrated in Fig. 19. The plain bar represents the original shape from which all other forms were worked. In one case the ends of the bar were folded over and then welded together, while in another the metal forged like wrought iron The remaining forms were deformed without heating

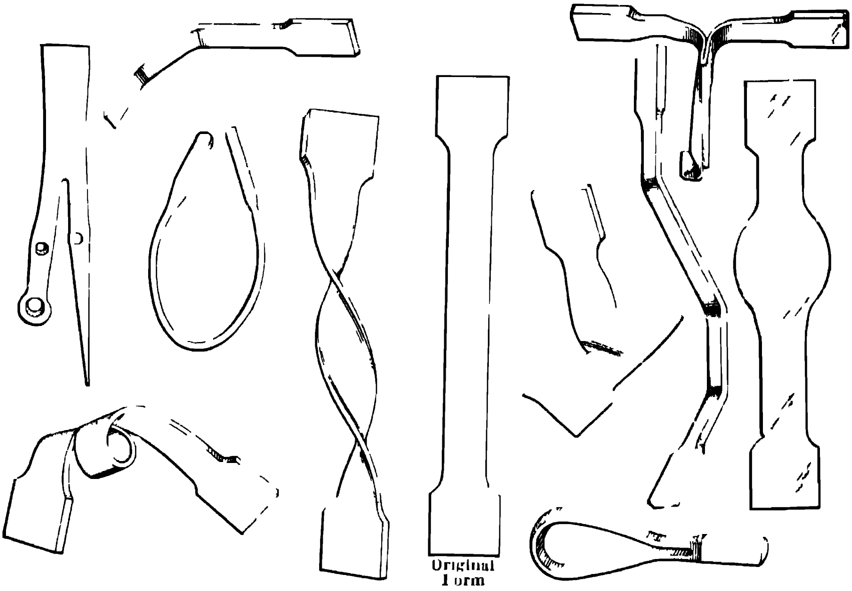

FIG. 19.—Examples of Cold-bending, Forging and Welding of Malleable Cast-iron Specimens, all being Originally like the Undeformed Bar in the Center (*Berlin Testing Laboratory Communications*, Vol 4, Pl 3)

CHAPTER XXVI

NON-FERROUS METALS AND ALLOYS *

COPPER

780. Production of Copper.—Copper ores are among the most widely disseminated. Valuable deposits are found in nearly all countries of continental Europe, in Japan, Chile, Mexico, Canada, Spain, Peru, Australia and Africa. The United States, however, produces about two-fifths of the world's supply. The states which lead in the production of smelted copper are: Arizona, Utah, Montana, Nevada, Michigan, Alaska, and New Mexico.

In general, copper ores carry a much larger proportion of earthy material than the ores of iron and rarely contain more than 10 or 15 per cent of copper. The three principal groups of copper-bearing ores in order of importance are: The sulphides, native copper and the oxidized ores. Among the sulphides *chalcopyrite* ($CuFeS_2$, 34.5 per cent copper) and *chalcocite* or *copper glance* (Cu_2S, 79.8 per cent copper) are the chief minerals. Native copper is very extensively mined in northern Michigan; it is also found in New Mexico, Peru and China. In the Michigan deposits, native copper is found scattered through the lodes in particles of widely varying size. It constitutes up to 4 per cent of the ore mined and is generally very pure, although occasionally contaminated with arsenic; it is often called "Lake" copper. The oxidized ores are derivatives of the sulphides which have been broken down by the action of air and water. The more important are: *Cuprite*, the red oxide of copper (Cu_2O, 88.8 per cent copper), and the green carbonate, *malachite* ($CuCO_3+Cu(OH)_2$, 57.3 per cent copper).

Nearly all copper is extracted by smelting; a small proportion is derived by wet methods in which the copper is withdrawn from the ore in the form of a sulphate or chloride. The oxidized ores are readily smelted in a special type of blast furnace using coke as fuel. Lake copper ores are first concentrated to form a mineral containing 70 per cent or more copper, which is then smelted in a reverberatory furnace. The sulphides, however, require a more complicated treatment, since it is not possible to reduce them directly to metallic copper. Smelting of the sulphide ores is commonly done as follows: The coarse lumpy ore is smelted in a blast furnace with or without previous roasting of a whole or part of the ore charged. The fine portions are usually roasted in reverberatory furnaces. These operations serve to concentrate the copper of the ore into a matte consisting principally of copper and iron sulphides with more or less of the sulphides of nickel, zinc, silver, and lead. Removal of the major portion of the iron and sulphur compounds is effected by placing the molten matte in a converter and oxidizing it with an air blast which enters just above the bath. After the smelting operation the crude copper ("blister copper") is cast into small pigs.

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* References: *The Metallurgy of the Non-Ferrous Metals* by W. Gowland, *Alloys and Their Industrial Applications* by E. F. Law, *Metallic Alloys* by G. H. Gulliver.

Refining of the crude copper may be accomplished by melting in a reverberatory furnace, or electrolytically. Refining in the reverberatory furnace is brought about by further oxidation of sulphides and by the cleansing action exerted by cuprous oxide on the base metals in the crude copper, the oxide being formed by air blown upon the molten bath. Since a large excess or a deficiency of cuprous oxide in the copper will make it weak and brittle it is necessary to remove any excess which remains after the impurities have been skimmed off. This is accomplished by additions of charcoal, and greenwood to the bath until the fracture of test ingots presents a flat salmon-red surface of silky texture. The copper is then at "tough pitch" and is ready for casting. Fire refining is used to give crude copper the malleability, ductility and toughness essential in plates, tubes and wires. It is also used to refine copper for alloys and to partially refine metal for anodes in the electrolytic process.

Electrolytic refining is used when an especially pure grade is wanted for electrical purposes, also when there is a considerable quantity of gold or silver associated with the crude copper. It is accomplished by passing a current through a copper sulphate solution from an anode consisting of crude copper, or partially refined copper, to a cathode of pure copper. By this method pure copper from the anode is plated upon the cathode and the precious metals settle to the bottom of the bath.

Copper for electrical purposes should contain less than 0.1 per cent of impurities (silver being counted as copper). Copper for castings generally carries less than 1 per cent of impurities.

781. Properties of Copper.—Besides possessing high resistance to atmospheric corrosion and high electrical conductivity, copper may be made very strong or very tough and malleable by suitable treatment.

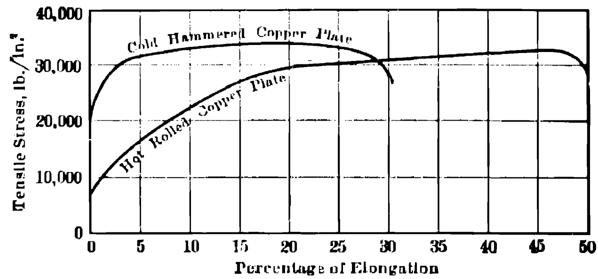

FIG. 1.—Typical Stress Diagrams for Copper Plate ½-in. Thick. (Martens, *Berlin Testing Lab. Communications,* 1894.)

The first and most general error to guard against in the matter of the strength of copper and its alloys is that of ignoring the mechanical treatment to which the material has been subjected. Thus, in the case of copper plate, as shown by Fig. 1, a hot-rolled plate has an elastic limit of only some 7000 or 8000 lb. per sq. in., with an elongation of 50 per cent, while the same plate, cold-hammered, has an elastic limit of over 20,000 lb.

per sq. in., with an elongation of 30 per cent. Both have an ultimate strength of about 33,000 lb. per sq. in. When simply cast, without rolling or forging, both the elastic limit and the ultimate strength are much less, but copper is seldom used in this way.

The combined effects of mechanical and heat treatment on strength and ductility are well illustrated in the process of wire drawing. Thus the strength of hard-drawn copper wire will vary from 50,000 lb. per sq. in. for wire 0.5 in. in diameter to 70,000 lb. per sq. in. for wire 0.05 in. in diameter and the elongation will decrease from approximately 4 to 0.9 per cent. When annealed, wire of the above sizes will have a strength of 35,000 to 40,000 lb. per sq. in. and an elongation of 35 to 25 per cent, being stronger and less ductile in the smaller sizes.

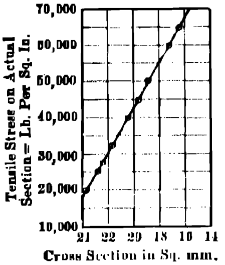

FIG. 2.

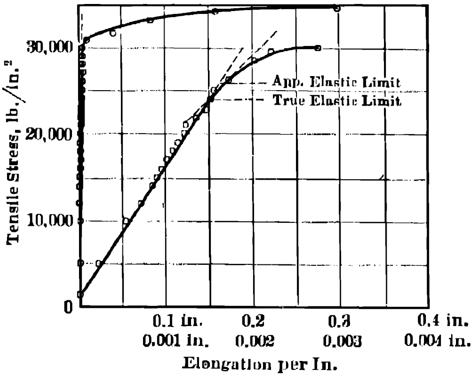

FIG. 3.

FIG. 2.—Showing a Linear Relation between Reduction of Area of Section and the Unit Stress on the Actual Section of Rolled Copper Plate ¼ in. Thick. (*Rept. French Com.*, Vol. 3, Pl. 4.)

FIG. 3.—Typical Stress Diagram for Drawn Copper. (*Tests of Metals*, 1886, Vol. 2, p. 1673.)

If the stress in a copper rod be computed for the actual cross-section at every stage of a tensile test, and the values so gotten be plotted against the diminishing cross-sectional area, the points will lie in a straight line, as shown in Fig. 2. This shows that the tenacity of copper increases regularly up to rupture with the reduction in area due to cold drawing.

The elastic limit of medium and hard-drawn copper wire lies between 50 and 60 per cent of its tensile strength. The metal does not, however, exhibit a well-defined yield point like steel, see Fig. 3. The modulus of elasticity of hard-drawn copper wire generally runs between 14,000,000 and 17,000,000 lb. per sq. in.

Hard-drawn copper may be annealed by heating to a temperature of 400° C. (752° F.). Rapid cooling does not interfere with softening of the metal but repeated alternations of overstrain and annealing at the higher temperatures cause a marked growth in crystal structure. Effects on strength of wire of heating to various temperatures and quenching are shown in Fig. 4.

The electrical resistivity of copper having less than 0.1 per cent of non-metallic impurities lies between 0.155 and 0.159 ohm per meter gram at 20° C. The resistivity increases with the content of impurities and with amount of wire drawing.

782. Uses of Copper.—The major portion of the copper produced in this country is used for electrical purposes on account of its high conductivity. About one-fourth is used in making brasses and bronzes, and a smaller proportion is rolled into sheets for roofing and sheeting, into tubes for condensers and for other conductors which must withstand corrosion and possess fair strength and flexibility. Copper is also cast and beaten into various ornamental forms.

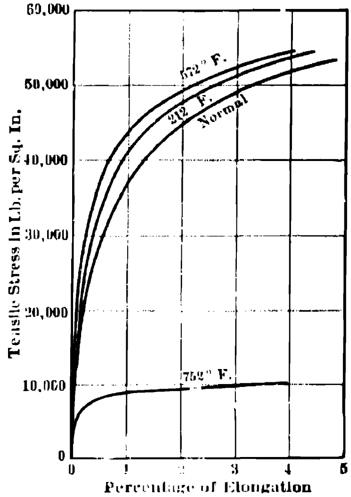

FIG. 4.—Effects of Heating Hard-drawn Copper Wires to Various Temperatures and then Quenching in Water. (Martens, *Berlin Testing Lab.*, 1894, Pl. I.)

ZINC

783. Production of Zinc.—Like copper most of the world's supply of zinc is obtained from sulphide ores, *zinc blende* or *black jack* (ZnS, 67 per cent zinc), which ordinarily carry from one-third to one-half zinc. The ores are very often found associated with the sulphides of lead (galena), iron (pyrites), and copper. The principal sources of supply are Belgium, Germany, Canada, Poland, and Great Britain, and within the United States—Oklahoma, New Jersey, Kansas, and Idaho. Zinc carbonate, *calamine* ($ZnCO_3$, 52 per cent zinc); the zinc silicates *Hemimorphite* and *Willemite*, and Franklinite (an ore of iron, manganese and zinc) form less important sources of supply. The carbonate is of chief importance in the Mediterranean countries while the silicates and Franklinite are the sources of an important supply in New Jersey.

The principal features in the extraction of zinc from its ores are the reduction of the sulphides and carbonates to the oxide form and the subsequent distillation of the oxide. The sulphide ores are finely ground and slowly roasted in reverberatory furnaces until nearly all of the sulphur is expelled. Carbonate ores and silicate ores are often calcined in shaft furnaces before being distilled. After roasting or calcination, the ore is mixed with a nearly equal amount of finely ground coal and shoveled into fire-clay retorts. By carefully controlling the temperature of the retorts at a white heat, carbon monoxide is produced and the zinc, thus relieved of its oxygen, is collected and cooled to liquid form in condensers. From time to time molten zinc is tapped from the condensers, skimmed and poured into molds. The zinc so cast is called spelter. Most of the spelter made in the United States is sufficiently pure for industrial purposes. When contaminated with lead or iron, it is further refined by melting at as low temperature as possible. By so doing a separation of these metals is effected through the differences in their specific gravities. In 1915 the electrolytic refining of zinc on a commercial basis was successfully begun at several places.

784. Properties of Zinc.—The most important property of zinc is, without doubt, its resistance to atmospheric corrosion. However, in order to make use of it for protective purposes, as in fruit jar covers, cans and battery zincs where it must be deformed into the shape wanted, zinc must possess considerable ductility and strength. Like most metals the strength and ductility of zinc are much influenced by composition, heat treatment, and mechanical work. Observations show that lead tends to make spelter roll easier but it also softens, weakens and reduces ductility. Consequently it should not exceed 0.1 per cent in spelter used for making cartridge brass or condenser tubes. Iron and cadmium embrittle and harden zinc and are, therefore, a detriment in spelter which is to be rolled or used for galvanizing. For such purposes the content of these elements in the spelter should be very low, probably not over 0.02 or 0.03 per cent.

Data for estimating the strength of cast zinc are afforded by the tests of Rigg and Williams * which appear in Table 1. They found that small differences in the casting temperature of the spelter and slight variations in the temperature of the cast-iron molds caused marked changes in the sizes of the crystals and in the tenacity of the specimens. For example, note the wide variation in the tenacity of the specimens of the first samples of Prime Western No. 1 and No. 2 spelters. The specimens having the maximum strength were much finer grained than those of minimum strength. Similar results were obtained in the transverse tests. In compression, however, the loads carried at a given deformation were far more uniform. The compression specimens also exhibited a high degree of plasticity which was wholly absent in the tensile specimens. Rigg and Williams attribute the high compressive strengths of the first samples of Prime Western No. 1 and Prime Western No. 2 to the high cadmium contents in these spelters.

The influence of the reduction in rolling on the tenacity of zinc was investigated by Prof. H. E. Moore.† He found, for example, that the tensile strength of the zinc, which was 9060 lb. per sq. in. when cast, became approximately 22,000 lb. per sq. in. when rolled into plate 1 in. thick, and 25,000 when rolled into sheets 0.006 in. thick, both being pulled in the direction of the rolling. The strength across the grain (transverse to the rolling) was somewhat higher, especially for very thin sheets, than the strength in the direction of the rolling, but the ductility was pronouncedly lower. In the direction of the rolling the elongation in 8 in. varied from 4.85 to 21 per cent for specimens ranging in thickness from 1 in. to 0.006 in.

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* *Proc. A. S. T. M.*, Vol. 13, Pt. 19.

† *Bulletin* No. 52, Engr. Expt. Sta. University of Ill.

Zinc either cast or rolled shows no well-marked yield point. Moore found the limit of proportionality in tension varied from 2900 to 5800 lb. per sq. in. for the specimens he tested but nearly all of his specimens exhibited permanent set at much lower stresses.

TABLE 1.—THE STRENGTH OF CAST ZINC (Riggs and Williams)

Most of the values represent four tests, some only three. **Tension test-pieces were like Fig. 3c' Ch. III, with 1-in. gage length.** Transverse specimens were 1¼-in. cylinders 15 in. long with 12-in. span. They were not machined. Compression specimens were 1 in. in diameter and 2.6 in. long. All test-pieces were gotten from 1¼-in. cylindrical rods 17½ in. long cast on end in cold iron molds. In all cases the upper 2½ in. of the castings were discarded.

Grade of Spelter	Sample No.	Analysis, Per Cent. *Pb*	Analysis, Per Cent. *Fe*	Analysis, Per Cent. *Cd*	Mean Strength, Lb./in.² Tension	Mean Strength, Lb./in.² Compression at 20%, Deformation	Mean Strength, Lb./in.² Modulus of Rupture	Maximum Deflection on 12-in Span	Maximum Variation from Mean in Per Cent. Tension	Maximum Variation from Mean in Per Cent. Compression	Maximum Variation from Mean in Per Cent. Mod. Rupt.
High grade	1	.041	.014	.000	6,262	24,230	11,630	0.25	35	3	5
High grade	2	.040	.016	.000	4,330	23,640	10,570	0.25	15	2	5
Intermediate	1	.194	.016	.000	4,340	23,030	10,160	0.30	25	5	5
Intermediate	2	.190	.017	.000	5,095	23,150	12,360	0.31	19	4	20
Brass special	1	.474	.013	.000	11,980	28,070	16,550	0.29	20	3	34
Brass special	2	.484	.031	.000	4,330	24,830	13,110	0.21	24	5	35
Prime Western No. 1	1	1.19	.032	.250	7,710	38,770	11,020	0.13	46	0.3	23
Prime Western No. 1	2	1.42	.087	.079	3,700	29,970	10,050	0.13	19	5	7
Prime Western No. 2	1	.68	.010	.274	10,800	39,490	16,250	0.18	34	2	18
Prime Western No. 2	2	1.15	0.11	.046	4,670	28,450	10,370	0.19	22	6	9
Dross		2.09	3.51	.043	7,340	34,380*	15,300	0.05	13	11	10

* Failed completely.

Moore found the average ultimate shearing strength of eleven specimens of rolled zinc in punching tests was 19,400 lb. per sq. in. and for twelve specimens in double shear 17,100 lb. per sq. in.

From a large number of tests by Moore, the modulus of elasticity of rolled zinc lies between 10,000,000 and 15,000,000 lb. per sq. in., averaging about 12,000,000 lb. per sq. in. Six tests on cast zinc in tension gave

11,025,000 lb. per sq. in. Four tests on cast zinc in compression gave an average modulus of only 6,900,000 lb. per sq. in.

785. Uses of Zinc.—As a protective coating zinc is much used on iron and steel plate, boiler tubes, fruit jar covers, cans for resisting corrosion. It is used in making shoe nails, zinc etchings and the negative pole pieces of batteries. As a constituent of brass, German silver and some of the bronzes, zinc is also much used.

ALUMINUM

786. Production of Aluminum.—Aluminum is derived from bauxite of which the principal constituents are hydrated oxides of aluminum and iron with some silica. France, Hungary, United States, Jugoslavia, Dutch Guiana, and Italy lead in bauxite production. In this country Arkansas, Alabama, and Georgia are the producing states. Between 30 and 35 per cent of aluminum is the proportion generally found in the ores which are being mined.

The first step in the process of extraction of aluminum is the production of its oxide alumina from bauxite. Alumina is obtained by roasting the coarsely granulated bauxite at a temperature sufficient to drive off the water from the iron oxide. The treated bauxite is then finely ground and heated under pressure for several hours with a solution of sodium hydrate. This solution is diluted and filtered and a little sodium hydrate added to the filtrate. It is then agitated for several hours to precipitate the hydrate which is separated, washed, and calcined at a temperature of approximately 1000° C. The process results in the production of alumina with perhaps 1 per cent of the oxides of sodium, iron and silicon as impurities.

Aluminum is extracted by electrolytic decomposition of alumina in a molten bath of cryolite (a fluoride of alumina and sodium). The cryolite is placed in a shallow rectangular hearth provided with a coke bottom which serves as the cathode, and several vertical carbon rods suspended in the bath, which serve as anodes for the electric current. After the cryolite is introduced into the furnace and melted by the passage of the electric current, the alumina is thrown onto the bath. As it melts it is dissociated into aluminum and oxygen, the former settling onto the cathode at the bottom of the bath while the oxygen goes to the anodes and, forming carbon monoxide, escapes from the bath. From time to time a portion of the aluminum is tapped from the furnace and alumina and cryolite are added to replenish the bath. The metallic aluminum thus obtained usually contains from 0.2 to 2 per cent of silicon and iron as impurities. "Pure," or No. 1, aluminum usually carries about ½ per cent of these impurities.

Refining of alumina is done principally in the United States, Germany, U. S. S. R., Canada, France, Switzerland, and Italy. The production of aluminum is increasing very rapidly, especially in the United States and Germany. The entire production of the world is nearly 500,000 tons.

787. Properties of Aluminum.—Aluminum is a white metal of high metallic luster. It is harder than tin, having in rolled form a hardness of approximately 40 on Brinell's scale. Being second only to gold in malleability, it can be rolled into sheets 0.0005 to 0.0006 in. in thickness and may be hammered into leaves much thinner. Aluminum is one of the lightest of the metals of construction and, in proportion to its weight, very strong. The specific gravity ranges from 2.56 for castings to 2.7 for the densest types of mechanically worked parts. It is less ductile than copper but excels zinc, tin, and lead in this respect. The results given in Table 2

TABLE 2.—TENSILE PROPERTIES OF ALUMINUM
(Alloys Research Committee)

Composition:—Al = 99.53 – 99.54, Si = 0.24 – 0.31, Fe = 0.12 – 0.14 per cent.

Condition of Metal.	Strength in Lb./in.^{2} at		Per cent Elongation in 2 in.	Per cent Reduction in Area.
	Maximum Load.	Yield Point.		
Cast (cooled slowly)	10,270	4,260	1.9	27.3
Cast (cooled quickly)	11,310	5,380	22.0	33.8
Cast in chills	11,700	5,150	37.0	60.7
Rolled to $1\frac{1}{4}$-in. round bars	14,560	9,850	35.5	79.3
Rolled to $\frac{13}{16}$-in. round bars	16,130	14,570	30.5	81.2
Cold drawn to $\frac{13}{16}$-in. diameter	19,500	19,050	19.5	73.3
Cold drawn to $\frac{13}{16}$-in. diameter and annealed	16,620	15,690	23.0	82.0
			In 3 in.	
Rolled into sheets $\frac{1}{4}$-in. thick	18,750	17,700	10.6	
Rolled into sheets $\frac{1}{4}$-in. thick and annealed	13,240	6,050	41.0	
Rolled into sheets $\frac{1}{10}$-in. thick	20,290	19,270	6.3	
Rolled into sheets $\frac{1}{10}$-in. thick and annealed	13,220	6,720	31.0	
Rolled into sheets $\frac{1}{20}$-in. thick	20,450	18,820	3.7	
Rolled into sheets $\frac{1}{20}$-in. thick and annealed	13,060	7,170	36.3	

show the tensile properties of pure aluminum as determined by the Alloys Research Committee.* When hard-drawn into very fine sheets or wire the ultimate tensile strength may reach 40,000 to 50,000 lb. per sq. in. The compressive strength of cast aluminum in cylindrical specimens with length twice the diameter is 12,000 per sq. in. and the elastic limit 3500 lb. per sq. in. according to reports of the Aluminum Company of America.† The modulus of elasticity of cast aluminum is approximately 9,000,000 lb. per sq. in.

The coefficient of electrical conductivity of aluminum is about 62, silver being 100. On account of its light weight, a bar of given length is twice as good a conductor as a copper bar of the same length and weight. However, owing to the superior resistance of copper to repeated stress and its lower coefficient of thermal expansion, it is generally preferred to aluminum for transmission purposes.

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* See Eighth Report, *Proc. Inst. Mech. Engr.*, 1907, Pt. 1, p. 57.

† See *Properties of Aluminum*, published by the company.

Aluminum castings contract about 0.2 in. per foot in cooling from the molten state and are quite brittle (hot short) when solidifying. Aluminum may be cast either in sand or chill molds. With sand molds great care must be exercised to use sand as dry as can be worked and to avoid hard ramming of molds and cores. In pouring, the temperature of the metal must be kept as low as possible and the rate of pouring must be very slow. Aluminum castings are quite open grained, consequently due allowance for porosity must be made in designing the thickness of cylinder walls and pressure tanks to be made of it.

Aluminum parts can be annealed by gradually heating to temperatures between 350 and 500° C. and allowing them to soak for a short time at the temperature which has been found suitable for the given class of work.

According to manufacturers statements,* aluminum is highly resistant to the attack of nitric acid, is slowly dissolved by concentrated sulphuric acid and is soluble in hydrochloric acid. At ordinary temperatures sulphur, carbolic acid, salt water, vinegar, sea water, carbonic oxide, and sulphuretted hydrogen do not attack it; but it is rapidly corroded by the caustic alkalies.

788. Uses of Aluminum.—On account of the softness and porosity of aluminum castings and the superiority of its alloys with copper or zinc, little aluminum is used in cast form. However, it can be worked at much lower temperatures than iron or copper; and, inasmuch as its density and mechanical properties are greatly improved by rolling, heating, drawing, extruding or drop-forging, it is much used after such treatment. Very light tubing and wire are drawn from extruded sections of aluminum. It is rolled into sheets which in turn, may be stamped into a variety of shapes, in many cases without annealing.

Aside from the uses mentioned, aluminum is employed for portions of automobile bodies, for cylinders and pistons in automobile and aeroplane engines, for tips on bullets, for rivets, and kitchen utensils.

LEAD, TIN AND NICKEL

789. Lead.—Nearly all lead is derived from ores containing lead sulphide, *galena* (PbS, 86.6 per cent lead). Lead carbonate, *cerussite* ($PbCO_3$), and lead sulphate, *anglesite* ($PbSO_4$), are formed by decomposition of galena and sometimes constitute the outcropping portions of the galena ore deposits. Lead ores are comparatively lean, averaging in the United

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* See *Properties of Aluminum.*

States about 5 to 6 per cent of lead. The United States, Spain, Germany, Mexico and Australia normally produce over four-fifths of the world's supply of lead. Within the United States the chief sources of lead are Missouri, Idaho, Utah, and Montana.

Lead is extracted from its sulphide ores, generally in two steps. The preliminary operation consists in reducing the sulphur content by roasting the raw ore in pots or sintering it in shallow pallets. It is then smelted in a blast furnace. The products of the blast furnace are: lead bullion, containing more or less antimony, arsenic, copper, iron, silver and gold as impurities; a matte carrying copper and the remainder of the lead; sometimes a speise containing arsenides of iron and traces of the precious metals; and slag. If the bullion carries much of the impurities or the precious metals it is refined in reverberatory furnaces. The matte and speise are further treated to remove the lead which they carry.

Lead has a blue gray color and exhibits a dull metallic luster when freshly fractured. Exposure to moist air causes oxidation and loss of luster. Lead is so soft that it may be scratched with the finger nail and so malleable that it can be readily rolled into very thin sheets as in thin foil. It lacks ductility, however, and cannot, therefore, be drawn into fine wire. Lead is formed into pipes with hydraulic presses which extrude the hot metal through dies. Both the softness and the specific gravity of lead are reduced by the presence of the common impurities antimony, arsenic, zinc and copper. Magnesia, however, has a still more powerful hardening influence, only 2 per cent being required to raise the Brinell hardness of pure lead from about 6 to 20. Pure lead pigs have a dull, dead sound when struck with the hammer, but the presence of impurities increases resonance. Lead castings shrink about $\frac{5}{16}$ in. per foot in cooling.

The tenacity of cast lead generally lies between 1500 and 2000 lb. per sq. in.; in hard lead wire the strength may reach 3000 lb. per sq. in.

For the manufacture of sheets, pipes, solder, pewter and white lead a pure grade of lead containing less than 0.1 per cent impurities is wanted. For bearing metals and some of the alloys, hard lead which carries from 15 to 20 per cent of antimony is often used.

790. Tin is obtained in the Federated Malay States, Bolivia, Dutch East Indies, Siam, England, Australia and Africa from the black oxide of tin, cassiterite (SnO_2, 78.6 per cent tin). The total output of tin is about 170,000 tons annually. The principal deposits of the ore are found in alluvial sands, whence the name stream tin, and in veins or lodes, called lode tin. Stream tin deposits commonly contain less than 1 per cent, whereas the lode ore carries about two-thirds tin.

Stream tin ores are concentrated by washing and roasting processes and lode ores are crushed. Ores containing large amounts of sulphur or arsenic are roasted to oxidize these impurities. After these preliminary treatments the dressed or roasted ore is smelted at a high temperature (1000° C.) in a reverberatory furnace, or, if the ores are very pure, a blast furnace is sometimes used. The crude tin thus produced carries more or less iron, copper, lead, arsenic, antimony, and tungsten. Since many of the alloys of tin and its impurities have higher melting-points than the pure metal, the latter can be separated by raising the temperature of the crude tin just above the melting-point of pure tin. Further refining is brought about by aerating the molten tin through violent agitation, thus producing more complete oxidation of the impurities. This is accomplished by submerging logs of greenwood in the bath of molten tin (poling) or by repeatedly pouring the molten tin from ladles (tossing).

Considerable quantities of tin are now recovered by electrolytic and chemical methods from scrap tin plate.

The best grades of Asiatic tin carry less than 0.1 per cent of impurities; but the lower grades from China and Bolivia, and tin recovered from scrap, may contain from 1 to 5 per cent of impurities,—lead, antimony and copper being the principal associated metals.

Tin is a silvery-white, lustrous, and extremely malleable metal as is evidenced by its form in tin-foil. Its specific gravity is 7.3 and it melts at 232° C. but does not volatilize until the temperature is raised above 1200° C. Tin is harder, more ductile and somewhat stronger than lead. The presence of iron, copper, or lead renders tin harder and more brittle, whereas small percentages of arsenic and antimony reduce its strength and hardness. The ductility of cast tin is influenced by the casting temperature, too high or too low temperature causing brittleness. Reported values of the tensile strength of tin vary from 2500 to 5000 lb. per sq. in. In ductility it equals soft steel. Tin is somewhat stronger in compression than in tension.

The resistance of tin to corrosion has led to its use as a coating for thin sheets of soft steel. Sheets coated with pure tin, "bright" tin, are used to make cans, utensils and furnace pipes. Sheets coated with a lead-tin alloy, "terne" plates, are used for roofing. Considerable tin is also used in making the bronzes and other alloys and a small proportion is made into tin-foil.

791. Nickel is gotten almost entirely from two sources, the nickeliferous magnetic pyrites found in the Sudbury District of Ontario, Canada, and to some extent from the hydrated nickel-magnesium silicate of New Caledonia, an island east of Australia. The pyrite ore usually contains about 3 per cent nickel, 2 per cent copper, with iron and sulphur constituting the major portion of the residue. The silicate ores generally carry from 6 to 8 per cent of nickel. About 100,000 tons is the world's yearly production of metallic nickel.

In order to extract nickel from the sulphide ores, it is first necessary to roast the ore to reduce the sulphur content. The roasted ore is then smelted in a blast furnace and a crude matte of nickel, iron and copper is formed. By Bessemerizing this matte the iron is removed, leaving a more pure matte of copper and nickel sulphides. Nickel with 1 to 2 per cent of impurities may be obtained from the Bessemerized matte by smelting in a reverberatory furnace with coke and sodium sulphate. By this process the copper and iron are formed into a matte of lower specific gravity than nickel sulphide. The nickel sulphide is withdrawn from the bottom of the molten bath and resmelted until the desired purity has been obtained. It is then roasted to form nickel oxide which can be reduced to metallic nickel by smelting with charcoal in iron tubes.

The Bessemerized matte may be more completely purified by the Mond process. In the latter process the matte is first crushed, ground and roasted. The oxides are then treated with dilute sulphuric acid to remove the major portion of the copper. The residue is partially reduced by hot producer gas and volatilized at a lower temperature into nickel carbonyl. By passing the latter through a heated tower the pure nickel is deposited in granular form.

Nickel is a brilliant metal approaching silver in color. It takes a good polish and does not tarnish or corrode in dry air at ordinary temperatures. The melting-point of nickel is about 1500° C., its specific gravity is about 8.3, when cast, and 8.7, when rolled. Nickel, if attracted by a magnet, becomes magnetic but loses its magnetism when heated to 340° C. It is almost as hard as soft steel, far more malleable, and when rolled and annealed, is somewhat stronger and almost as ductile. Nickel is rendered brittle by the presence of small percentages of carbon, arsenic, nickel oxide and sulphur. Small amounts of magnesium render it more ductile and iron makes it hard. The tenacity of the metal ranges from 75,000 lb. per sq. in. for thin sheets of annealed nickel to twice that value for very fine hard-drawn wire.

Nickel is used chiefly in making nickel steel, coins, German silver, resistance wires, and in plating.

Monel metal is an alloy carrying about 66 to 68 per cent nickel, 2 to 4 per cent iron, 2 per cent manganese, and the remainder copper. It can be cast, forged, rolled, drawn into wire, electrically welded, soldered or brazed and is easily machined. The melting-point is 1360° C. and the specific gravity in cast form is about 8.87. The shrinkage of castings in cooling is about the same as for steel, ¼ in. per foot. Monel metal has about one-fifth the heat conductivity of copper and one-twenty-fifth of its electrical conductivity. In appearance it is not distinguishable from nickel. The tensile strength of Monel metal in castings is 60,000 to 80,000 lb. per sq. in., in hot-rolled bars 80,000 to 100,000 lb. per sq. in. The yield point is about 50 per cent of the ultimate strength in cast metal, and 75 per cent in rolled form. In ductility it compares favorably with soft steel, the elongation in 2 in. ranging from 18 per cent in cast metal to 40 per cent in rolled rods. The modulus of elasticity is approximately 23,000,000 lb. per sq. in.

Monel metal is highly resistant to corrosion and the action of sea water. This valuable property coupled with its great strength, ductility and toughness make it a very useful metal for propellers, pump rods and pump linings, roofing metal and for castings and wrought parts which must withstand attack of sea water or mine waters. Inasmuch as the metal costs about ten times as much as the steel, extended use has been limited by the expense involved.

BRASSES AND BRONZES

792. The Brasses—Copper-zinc Alloys.—The most valuable brass alloys contain from 60 to 90 per cent copper and 10 to 40 per cent zinc. The color of brasses ranges from a silvery-white for alloys carrying little copper to a copper-red for those containing little zinc. The color is also affected by the rate of cooling.

Brass may be either cast or wrought. Brass for castings usually contains from 30 to 40 per cent of zinc. The addition of 2 or 3 per cent of tin serves to increase hardness, but it also lessens ductility. One or 2 per cent of lead renders brass more easily turned, filed and polished, but reduces the ductility and strength; while 1 to 6 per cent of aluminum materially raises the strength but may lessen the ductility.

In all cases, when melting copper, brass or bronze, great care must be exercised to keep the air from the metal, in order to prevent oxidation. This is done by covering the metal, in the crucible, with a thick layer of powdered charcoal. The copper is first melted alone, in a deoxidized flame, and then the scrap brass and zinc (previously melted, these fusing at a much lower temperature) are added and the whole stirred vigorously to effect a thorough mixing. Sometimes this mixing is done after the crucible is removed from the furnace. If it is done in the furnace, the dampers should be nearly closed to prevent an excessive heat, which would vaporize the zinc. If iron molds are used they should be heated and the interior surfaces coated with a mixture of resin (3 pts.) and lard-oil (1 pt.) to prevent adhesion. In pouring, the metal must be very carefully skimmed. The pattern should be made to allow a shrinkage of $\frac{1}{4}$ in. per foot. For common castings green sand is used, but for fine work the molds are dried. The leaded brasses are poured quite hot and chilled rapidly, but the bronzes are poured at as low a temperature as possible and into heated molds in order to avoid contraction cracks.

The mechanical properties of cast brasses of all compositions are shown in Fig. 5. It will be observed that the commercial brasses are stronger and more ductile than either of their components, copper and zinc. Electrical conductivity for the brasses is, however, very much less than for copper, being only 0.20 for brass containing 70 per cent copper.

Brasses suitable for hot working, by forging, rolling or extruding, carry from 37 to 45 per cent zinc. Those which are to be extruded often contain 2 to 4 per cent of lead to make them flow easily through the dies. Lead, however, lessens the amount of reduction in working, which these alloys will withstand without cracking, makes the metal more porous and more susceptible to burning during melting. The brasses wrought into shape by cold working carry less than 40 per cent zinc, usually the ratio of copper to zinc runs between 2 to 1 and 3 to 1.

Brasses containing equal parts of copper and zinc are used principally for brazing brass goods. They have a very high crushing strength but are too brittle to be mechanically worked.

✓Alloys carrying 57 to 63 per cent copper, often called *Muntz Metals*, are used for bolts, rods, tubes and various extruded shapes. These alloys may be hot-worked but harden considerably when cold-worked and are very liable to season cracking. When slowly cooled from a cherry-red temperature these alloys have a tenacity of 55,000 to 65,000 lb. per sq. in. with an elongation in 2 in. of 50 to 60 per cent. The limit of proportionality is low, being in the vicinity of one-third of the ultimate strength.

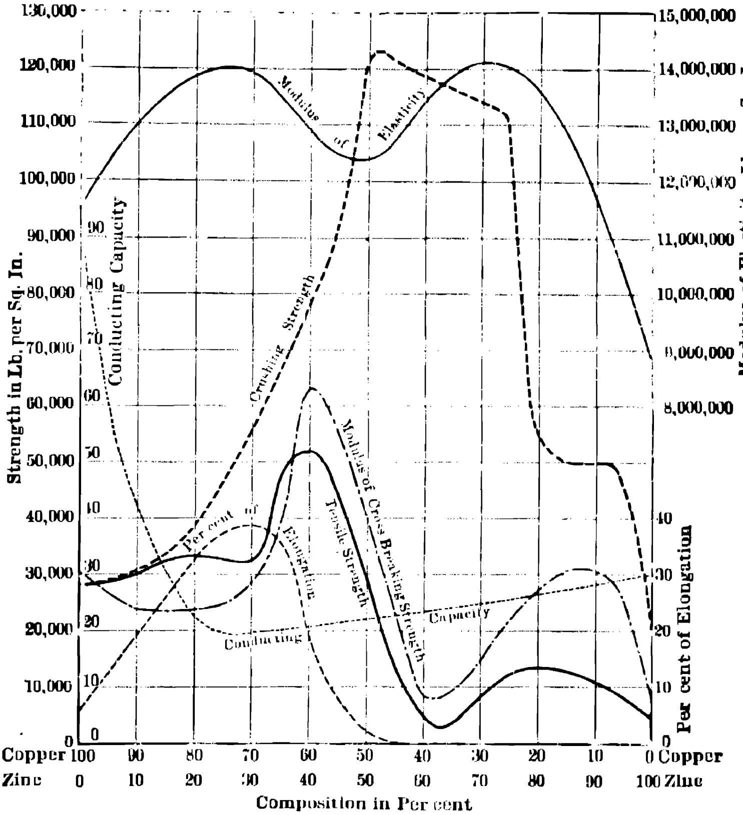

FIG. 5.—Properties of Cast Brass for Varying Proportions of Copper and Zinc. (Data from U. S. *Test Board Rept.*, 1881, Vol. 2.)

The strength, hardness and ductility of these alloys appear to be somewhat increased by quenching.

Perhaps the most useful brasses are those containing approximately 2 parts copper to 1 part zinc, often termed "common" or "standard brasses." They are used for sheets, wire, and many stamped and drawn articles. A notion of the wide range of properties exhibited by these brasses may be obtained by comparing the properties of castings, Fig. 5, with the plate specimens of Fig. 6 and the hard-drawn specimens subjected to various annealing treatments, Fig. 7. Brasses of this composition annealed at

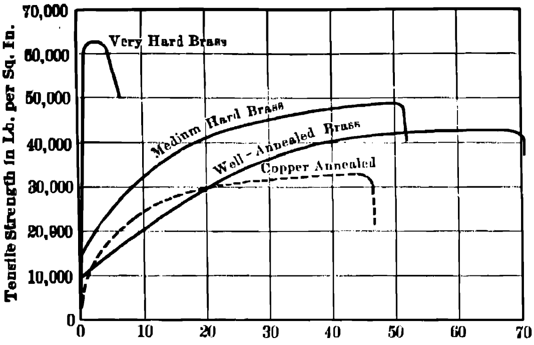

Fig. 6.—Stress Diagrams of Rolled Brass (Cu = 67 per cent, Zn = 33 per cent) and Copper. (*French Com. Rept.*, Vol. 3, Pl. 5.)

a cherry-red heat have a Brinell hardness number of 45 to 55; when hard-drawn the hardness may reach 150 to 160.

Brasses carrying 70 to 75 per cent copper find use in cartridge cases, condenser tubes, tubes for brazing and in spinning operations. They have good resistance to corrosion and excellent cold working qualities. In cast form, alloys of this composition are very ductile. Their strength and ductility are not materially changed by quenching. Cold working, however, raises the strength of the annealed brass from about 45,000 to 80,000 lb. per sq. in. but decreases the elongation in 2 in. from approximately 50 to 5 per cent.

With 80 to 95 per cent copper the brasses take a good polish and have a color somewhat like gold. They are used for medals, cheap jewelry and as gilding for percussion and primer caps. The tensile properties of a hard-drawn 90–10 brass under various annealing treatments are shown in Fig. 7.

793. Complex Brasses are alloys of copper and zinc with one or more other metals. The more important of these are manganese bronze, naval brass, sterro-metal, delta metal and Tobin bronze.

Manganese bronze is really a brass containing very small per-

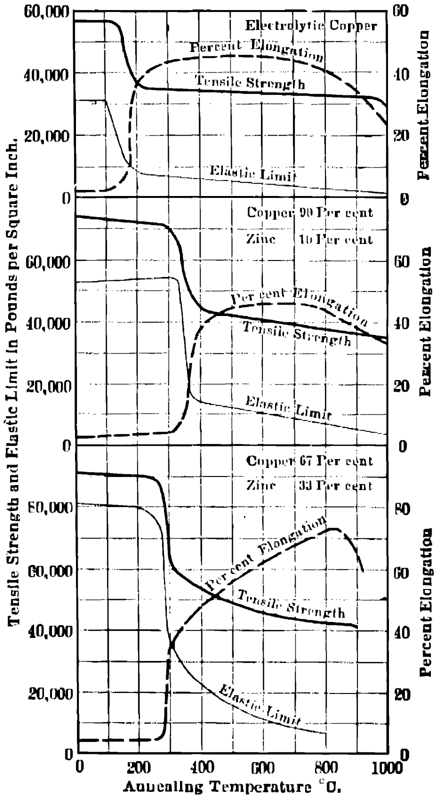

Fig. 7.—The Influence of Annealing on the Tensile Properties of Cold Rolled Copper and Brass (Grard, *Proc. I.A.T.M.*, 6th Congress II_{16}.)

centages of tin, iron and manganese. The usual range in composition is about as follows: Copper, 57–62; zinc, 36–40; tin, 0.5–1.5; iron, 0.5–1.0; manganese less than 0.5 and lead under 0.2 per cent. Besides exercising a deoxidizing influence while in the bath of molten metal, manganese, by virtue of its association with iron strengthens, hardens, and slightly embrittles the brass. Tin also increases hardness.

The tensile strength of cast manganese bronze ranges from 70,000 to 80,000 lb. per sq. in. with an elastic limit of about one-third of the ultimate strength. The elongation in 2 in. generally lies between 20 and 30 per cent. In rolled or forged form its strength is slightly increased, its elastic limit raised to 30,000 or 40,000 lb. per sq. in. and the elongation in 2 in. is raised to 30 or 40 per cent. In compression the strength runs from about 90,000 lb. per sq. in. for castings to 150,000 lb. per sq. in. for rolled or forged parts. The modulus of elasticity of manganese bronze is about 16,000,000 lb. per sq. in.

On account of its high strength, the facility with which it may be forged or rolled, and its resistance to corrosion and salt water, manganese bronze is used considerably in marine engine parts, for hydraulic rams, cylinders, valve stems, propeller blades and bolts, and condenser tubes. Wrought manganese bronze parts are subject to season cracking and should always be annealed.

Naval brass is used for similar purposes and is much like manganese bronze in composition but lacks manganese and iron. It is slightly weaker and more ductile than manganese bronze. The tenacity in wrought form ranges from 55,000 to 70,000 lb. per sq. in. with an elongation in 2 in. of 30 to 45 per cent. Naval brass is also subject to season cracking and should be annealed when used in wrought form.

Sterro metal is an iron-brass containing about 38 per cent zinc with 1.5 to 2 per cent iron and the remainder copper. It has been used for hydraulic cylinders working under heavy pressures.

Delta metal, which is an improvement on sterro metal, is a proprietary composition, or brass, placed on the market since 1883 by a Mr. Alexander Dick (England). His process consists in incorporating a *fixed* amount of iron by making first a saturated solution of iron (about 5 per cent) in molten zinc. To prevent oxidation a little phosphorus is added to the melted copper. The proportions are varied for different purposes, having from 50 to 65 per cent copper, 50 to 30 per cent zinc, 0.1 to 5 per cent iron, and sometimes 0.1 to 1 per cent tin. This metal is as strong and ductile as mild steel, having a tensile strength, when rolled and annealed, of 60,000 to 80,000 lbs. per sq. in. with elongations in 8 in. of 40 to 14 per cent, respectively, at these limits.* When cast in sand its tensile strength is 45,000 lb. per sq. in. with an elongation of 10 per cent. It is also highly resistant to corrosion.

Tobin Bronze is very similar to sterro metal and delta metal, the iron ingredient being somewhat less. Its composition is approximately 60 per cent copper, 38 per cent zinc, 1 to 2 per cent tin, with small portions (0.1 to 0.3 per cent) of iron and lead. Its remarkable properties are due to rolling and annealing. As placed on the market, its tensile strength is from 60,000 to 80,000 lb. per sq. in., with an elastic limit of 60 per cent of its ultimate strength, and an elongation of from 25 to 15 per cent in 8 in. at these limits, respectively. It may be regarded as having the strength and ductility of structural steel, with the advantage of being non-corrosive. It can be procured in sheets from $\frac{1}{16}$ in. to $1\frac{1}{2}$ in. thick, and in round rods from $\frac{1}{4}$ in. to 5 in. in diameter. Tobin bronze is readily forged at a cherry-red heat either by hand or by machinery, and also works well in the lathe. The elastic properties of this material are shown in Fig. 9.

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* Tests made at Lloyd's Proving House, as given by Hiorns.

794. The Bronzes—Copper-tin Alloys.—Since tin is added to copper principally to harden it,—it strengthens copper very little,—the copper-tin alloys may be regarded as a kind of hardened copper. The ancients used these alloys for their cutting-tools, and they are used now largely on account of their hardness and non-corrosive properties. The useful range of composition is 5 to 25 per cent of tin and 75 to 95 per cent copper.

In cast form the tensile strength of these alloys varies from 28,000 to 35,000 lb. per sq. in., maximum tenacity occurring for a tin content of about 18 per cent. The crushing strength of cast bronze rises from approximately 42,000 lb. per sq. in. for pure copper to a maximum of 150,000 lb. per sq. in. for bronze carrying 25 per cent of tin. The ductility of the bronzes is low. Cast bronzes carrying about 4 or 5 per cent of tin are the most ductile, elongating about 14 per cent in 5 in. With more than 5 per cent of tin the alloys lose most of their malleability when cold. The alloy having 12 per cent of the tin has an elongation in 5 in. of only 3 or 4 per cent and with 20 per cent tin it becomes practically nil. The tenacity also diminishes rapidly as the tin content of the alloy is raised above 20 per cent.

Gun metal is one of the strongest bronzes. It contains about 10 per cent tin and was formerly much used in casting guns. It is now used to some extent for strong castings. *Bell metal* is the hard sonorous bronze carrying about 20 per cent tin, used in making bells and gongs. By alloying 2 parts copper with 1 part tin a beautiful, hard, perfectly white metal is produced, called *speculum metal.* When polished this metal can be used for mirrors and reflectors.

795. Complex bronzes, are alloys of copper and tin with one or more additional metals. Among the more useful are zinc bronzes, phosphor bronzes, and lead bronzes.

The Copper-tin-zinc Alloys.—As shown in Fig. 8, the valuable ternary alloys are those in which copper forms the controlling element. This diagram is based on that principle in geometry which makes the sum of the normals from any point on the interior of an equilateral triangle equal to the altitude of the triangle. If the three altitudes be each taken as a scale of equal parts on which are indicated proportions (percentages) of copper, zinc, and tin respectively, these ranging from zero to 100, then to the same scale the sum of the three normals from any point in the triangle will be 100, and hence these three normals may be used to indicate the percentages of the three metals which unite to form the alloy which is represented by that point in the triangle.* An alloy of any two of these finds its place along one side of the triangle, of which the three apices make the 100-per-cent ends of the three metal scales. A little study of Fig. 8 will make this clear.

The contour-lines on this figure were drawn by J. B. Johnson after plotting on this triangle the tensile strengths of cast bronzes of known composition from all reliable sources. From an examination of this chart it is at once evident that only those alloys near the copper apex are of any value, the strongest being, however, near the copper-zinc side, where the composition is about 59 per cent copper, 39 per cent zinc and 2 per cent tin. The tensile strength of such a casting, if properly made, is about 60,000 lb. per sq. in. It is too brittle, however, to be of much value. The most valuable alloys are those having an ultimate strength of from 35,000 to

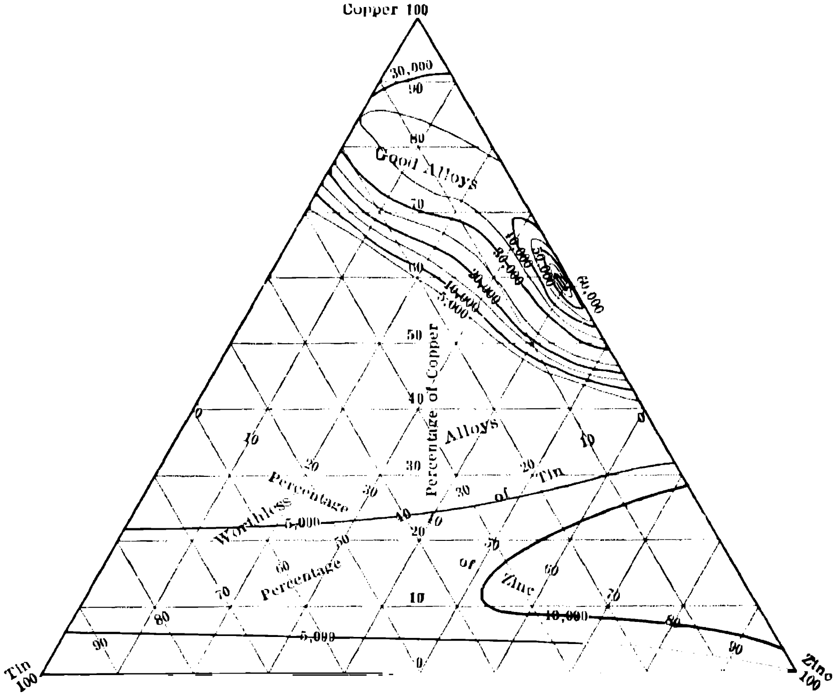

FIG. 8.—The Tensile Strength in Pounds per Square Inch of Copper-zinc-tin Alloys in Form of Castings. (Compiled by J. B. Johnson, from Records of U. S. *Test Board*, 1881.)

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* This method of representing these triple alloys was first used by Dr. R. H. Thurston, *Trans. Am. Soc. C. E.*, 1881.

40,000 lb. per sq. in. tensile strength, with 20 to 30 per cent elongation. This is found in the vicinity of 75 to 85 per cent copper, 17 to 5 per cent zinc, and 8 to 10 per cent tin.

It must be understood, however, that so much depends on the purity of the ingredients and on the manipulation of the process of melting and casting, that this chart, or any similar record, must be taken as showing what *may* be obtained rather than what *will* be obtained from the use of these particular mixtures.

✓*Government bronze* or *Admiralty metal*, consisting of 88 per cent copper, 10 per cent tin and 2 per cent zinc, is a zinc bronze much used for valves, fittings, gears, and nuts where good strength is wanted. This metal has, when cast in sand molds, a strength of 30,000 to 35,000 lb. per sq. in. with a poorly defined yield point of 15,000 to 17,000 lb. per sq. in. The elongation in 2 in. is about 14 to 16 per cent. When annealed for a half hour at a temperature of 700 to 800° C. the ductility of the metal is much increased but the tenacity is practically unchanged. Government bronze cast in sand molds is considerably more ductile than that cast in chills. The ductility of the latter may be greatly improved, however, by annealing, at the above-mentioned temperatures.* Government bronze is not a satisfactory metal for parts subjected to temperatures above 260° C.

✓*Phosphor bronze* is any copper-tin alloy made with phosphorus as a deoxidizer. Besides deoxidizing, it is also claimed that the phosphorus causes the tin to form a crystallized compound with the copper. It is mainly, however, as a cleanser of the melted metal from the oxide of copper that it is valuable. The phosphorus is added in the form of phosphor-copper or phosphor-tin, these containing phosphides of copper or of tin. For a malleable product, to be rolled or drawn into wire, the tin should not exceed 4 or 5 per cent, and the phosphorus should not exceed 0.1 per cent. For hard castings of great strength, as for pinions, valves, bearings, or bushings, use 7 to 9 per cent of tin and ½ to 1 per cent of phosphorus. A greater amount of phosphorus, up to 4 per cent, increases the hardness and brittleness. More than 4 per cent phosphorus will make the product useless.

Stress diagrams for phosphor bronze are shown in Figs. 9 and 10. The great toughness and high elastic limit of wrought phosphor bronze render it valuable for making springs which are subject to corrosion. The best grades of phosphor bronze carrying about 95 to 97 per cent copper, 3½ to 4 per cent tin and somewhat over 0.1 per cent phosphorus are used with good success in turbine blades.†

The United States Navy Department specifies for best grades of phosphor bronze castings a minimum tenacity of 45,000 lb. per sq. in. and an elongation in 2 in. of at least 20 per cent. The composition ranges for this metal are copper = 85 to 90, tin = 6 to 11, zinc < 4, iron < 0.06, lead < 0.2 and phosphorus < 0.5 per cent. This metal is used for gears, driving and main nuts on steering gears, and castings requiring good bearing qualities and high resistance to corrosion.

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* See *Technologic Paper* No. 59, U. S. Bureau of Standards.

† *Jour. Inst. Metals*, Vol. 14, p. 56.

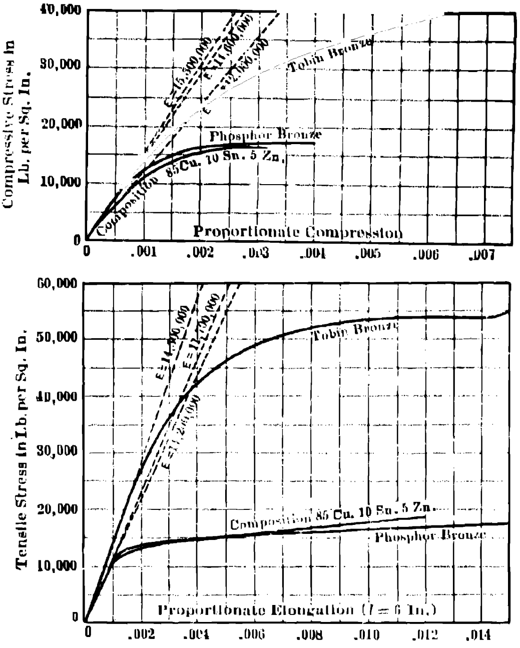

FIG. 9.—Results of Tension and Compression Tests on Three Alloys Used for Valve Stems. Tobin bronze specimens were rolled, others were plain castings. (Russell, *Jour. Assoc. Eng. Soc.*, Vol. 15, p. 207. Tests by J. B. Johnson.)

Lead bronzes are much used for bearings, under heavy pressures. In most cases these bronzes are smelted with a very small percentage of phosphorus and are called phosphor bronzes, although the amount of phosphorus remaining in the bronze is generally well under 1.0 per cent. When more than 3 or 4 per cent lead is present in bronze bearings it segregates, forming soft spots in the hard matrix which rapidly wear and form cavities for the lubricant.

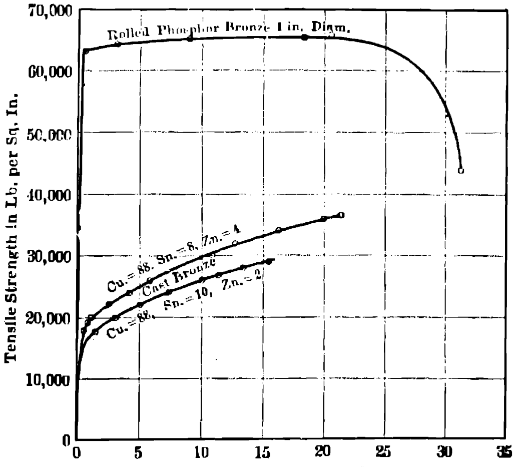

FIG. 10.—Tension Stress Diagrams of Cast and Rolled Bronzes. (*Tests of Metals*, 1885.)

For bearings in contact with hard steel and subjected to pressures over 1500 lb. per sq. in., phosphor bronze carrying about 80 per cent copper, 20 per cent tin, and less than 1 per cent phosphorus works well. It is, however, unsuited to high speeds, since it is likely to run hot. This metal is suited for turntable bearings and center bearings on swing bridges. For heavy trunnion bearings in contact with soft steel carrying less than the above pressure and operating at slow speeds the copper content may be raised to 83 or 85 per cent. A very common mixture for accurately lined machinery bearings is the 80–10–10 of copper, tin and lead with less than 1 per cent phosphorus. This bronze is easy to manipulate but heats and wears more than Dr. C. B. Dudley's "Alloy B," consisting of 77 per cent copper, 8 per cent tin and 15 per cent lead. On the other hand the lead in the latter alloy has a pronounced tendency to segregation during pouring and much skill is required to secure good bearings with it. It is used by the Pennsylvania Railroad for car journal bearings.

796. Cold Working of Brasses and Bronzes.—As with the ferrous metals so with the non-ferrous, cold working causes densification of the metal, decreases grain size, promotes an increase in tenacity, and decreases ductility. Thus Davis * has shown that sheet brass (2 Cu to 1 Zn) varying from .01 to .06 in. in thickness increases in strength directly with the per cent reduction in area produced by rolling. For a reduction in area of 60 per cent the average strength was doubled, the per cent elongation in 2 in. was decreased to between $\frac{1}{10}$ and $\frac{1}{15}$ of the normal value, and the ductility as measured by the cupping test (Art. 798) was reduced to about $\frac{1}{5}$ of its normal value. Further examples of the effect of cold rolling and cold drawing of the non-ferrous metals appear in Figs. 2, 6, 7 and 14. It is probable that cold drawing causes more dangerous internal deformation within parts which are to withstand tensile stress than cold rolling or hammering, since cold drawing produces tensile stress in the surface layers and compressive stresses within, whereas stresses of opposite character are set up by cold rolling or by hammering. The magnitude of the internal stresses so produced is quite variable ranging from 3000 or 4000 lb. per sq. in. to 50,000 or 60,000 lb. per sq. in.† When above 5000 or 10,000 lb. per sq. in. such stresses seriously impair the strength of the metal. Steps should, therefore, be taken to remove internal stress by annealing or springing as mentioned in the next article.

Although there are, in general, internal stresses—necessarily of opposite sign—induced by cold working, the results gotten by E. H. Peirce ‡ working on hard-drawn copper wire show that the hardening effect of such treatment is practically uniform throughout the mass of the metal and is not confined to the skin as has sometimes been stated.

797. Season cracking § is a type of failure common to rods, tubes, sheets, cartridge cases and other articles made of brass or bronze. It is especially prevalent in brasses containing 60 to 80 per cent copper, in manganese bronze, Tobin bronze, and has been observed in aluminum and aluminum bronze. It may take place when the part appears to be under no stress; it may occur in a bolt or rod after it has carried a normal load for a considerable time, or it may happen when the brass is put into the annealing oven. The essential cause of "season cracking" is initial internal stress—produced by cold work, by burning in of defects, by quenching or by cooling strains induced in molding, coupled with one or more of the following:

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* *Proc. A. S. T. M.*, Vol. 17, p. 165.

† See *Technologic Paper No.* 82, U. S. Bureau of Standards.

‡ *Proc. A. S. T. M.*, , Vol. 17, p. 115.

§ See E. Heyn in *Jour. Inst. Metals.*, Vol. 12, No. 2, p. 3; *Technologic Paper* 82, U. S. Bureau of Standards; *Topical* Discussion in *Proc. A. S. T. M.*, Vol. 18.

(*a*) Corrosion, the metal being under no external stress;
(*b*) Applied stress of less intensity than the normal elastic limit;
(*c*) Temperature changes.

Although acting in different ways these combinations effect an overstressing at a certain region in the metal and cracking finally ensues. Considering the predominating cause of failure, "corrosion cracking" seems a more exact term to apply to the phenomenon.

Season cracking may be avoided by proper annealing, or by springing or by a combination of springing and annealing. Annealing at low temperature effects a removal of the greater part of the internal strain without producing material loss in hardness or strength. Indeed there is evidence to show that, in some cases, such annealing raises these properties.* To be effective in preserving high strength and good ductility the annealing temperature must be less than the temperature at which grain growth begins in the metal. This temperature varies inversely (but not in direct ratio) with the amount of permanent deformation which the metal has suffered and with the time the metal is held at a given temperature. For brasses containing 2 parts copper to 1 part zinc the range of annealing temperature which is effective in relieving initial stress without diminishing hardness is 200 to 300° C.

Springing consists in bending a bar backwards and forwards in radial planes until all outer fibers have been permanently lengthened. This treatment reduces the intensity of tensile stresses which exist at the surface in cold-drawn bars, and is sometimes a necessary preliminary treatment to prevent cracking of parts in annealing.

798. Special Tests for Brasses and Bronzes.—On account of the large internal stresses present in many cold-rolled and hard-drawn objects of brass and bronze and the harm which may come from them, simple tests for their detection are needed. The most precise method with a rod or tube specimen consists in making accurate measurements of length on three or more surface elements, turning off or boring out a predetermined amount of metal and measuring again. Knowing the modulus of elasticity of the metal, the cross-sectional area before and after machining, and the original length, it is possible to compute the unit stress in each layer removed. Since this method necessitates taking a large number of readings with a comparator or strain gage and since the machining cuts must be very small and slowly and accurately done, it requires too much time for commercial purposes.

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* Mathewson and Phillips, *Trans. A. I. M. E.*, Vol. 54, p. 608.

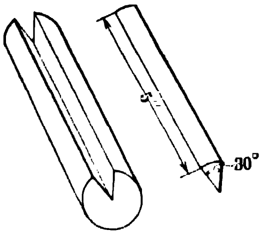

Fig. 11.—Miller's Specimen for Measuring Initial Stress in Brass Rods.

A more rapid method of measuring the internal stress in a bar has been devised by Mr. S. W. Miller. A specimen is cut from the straight bar, which is to be examined, as shown in Fig. 11. If the outer surface of the bar was in tension that surface of the specimen will be concave after its removal from the bar, the reverse would be true if the stress was compression. By measuring the mid-ordinate to the curve, assuming circular curvature and the neutral plane passing through the gravity axis the change in unit stress on the outer and inner fibers may be computed from these formulas:

$$S_0=\frac{8Efr}{3l^2} \quad \text{and} \quad S_1=\frac{16Efr}{3l^2}.$$

Here S_0 and S_1 = changes in unit stress at the outer and inner fibers respectively;

E = modulus of elasticity;
f = deflection at center of specimen;
r = radius of rod;
l = length of rod.

For thin sheets the procedure advocated by Merica and Woodward * is still more simple. A strip about 6 in. long and $\frac{1}{2}$ in. wide is coated with paraffin excepting one of the broad surfaces and etched with acid until one-quarter the depth is removed. If the strip curves the mid-ordinate of the arc is measured and the average value of the original internal stress is computed from

$$S=\frac{36tEf}{7l^2},$$

where t = original thickness of strip, f = mid-ordinate of arc after etching, and other symbols have same meaning as before.

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* Topical Discussion on Season Cracking of Brass, *Proc. A. S. T. M.*, Vol. 18, Pt. 2

Detection of the presence of high initial tensile stresses in the surface layers of a piece of brass may sometimes be accomplished by immersing the part in a solution of mercurous nitrate (65 gr. $HgNO_3$ and 15 cc. conc. HNO_3 per liter) for fifteen minutes to a half hour.* Badly strained pieces will frequently crack after this procedure.

The cupping test has recently been strongly advocated † for determining the ductility and drawing qualities of thin sheet metal, especially brass. The test is made on a small sample of metal supported between a die and annular holder. A round-nosed tool is gradually forced against the specimen and forms it into a cup as shown in Fig. 12. By determining the depth of the cup at fracture, a direct measure of the drawing quality of the metal is obtained. Davis claims that this rapid test is far more accurate than the tensile test or scleroscope hardness test. It is also superior to the Brinell ball test for brass sheets under 0.05 to 0.08 in. thick. The Brinell test, however, is very satisfactory for determining the drawing qualities of thicker sheets. He also states that the roughness of the surface of the cup and the character of the fracture afford evidence of the grain size and will reveal defects.

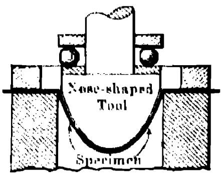

FIG. 12.—Showing Arrangement of Specimen, Tool and Dies on Erichsen Cupping Machine. (*Proc. A.S.T.M.*, Vol. 17, Pl. 2, p. 200.)

ALLOYS OF ALUMINUM

799. Utility of Aluminum Alloys.—Owing to the softness of pure aluminum, it is commonly alloyed with copper or zinc to improve its mechanical properties. About one-fourth of the entire aluminum production is now utilized in making light, stiff alloys with these metals, a large portion of which are used in the automobile industry. Thus we find the light aluminum copper alloys used for pistons, cylinders and crank cases for both automobile and aeroplane engines, also for cooking utensils and strong light parts which are die cast. The light alloys of aluminum and zinc are used to less extent for gear cases, light castings of high strength, and for portions of scientific instruments requiring lightness and rigidity. With small additions of manganese and copper the aluminum zinc alloys have been used in the frames of Zeppelins. The heavy aluminum bronzes find use in steam valves, pump rods, spindles, springs, propellers, motor and engine gears where good strength and resistance to corrosion are essential qualities.

800. Aluminum Bronze is the rather inappropriate name applied to copper-aluminum alloys containing less than 11 per cent of aluminum. It is made from the finest grades of copper and pure aluminum and is said to be improved by resmelting. On account of the rapidity with which aluminum oxidizes, the alloys must be smelted under a layer of charcoal and should be poured into the molds with as little agitation as possible. Castings must be provided with large gates and risers to provide against excessive shrinkage.

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* *Technologic Paper* 82.

† C. H. Davis, *Proc. A. S. T. M.*, Vol. 17, p. 165.

The ductility of the aluminum bronzes is very high and nearly constant for variations in aluminum content up to 7.3 per cent. Bronzes with more than 7.3 per cent aluminum show decrease in ductility as the aluminum increases and those containing 12 per cent are very brittle. The tenacity of these bronzes, however, increases directly with the aluminum content up to approximately 10 per cent aluminum. The tensile properties of these alloys * are shown in Fig. 13. It will be observed that the ductility of small castings of these alloys is about the same as in the rolled rods. The bronzes containing less than 7.3 per cent aluminum are highly resistant to torsional stress and readily rolled, forged and cold-drawn. Since they consist of a solid solution, the rate of cooling influences their mechanical properties very little. Bronze with 7.3 per cent aluminum exhibited great toughness under impact and remarkable resistance to alternate bending stress.

Bronzes containing over 7.3 per cent aluminum contain, besides the solid solution, a dark needle-like constituent, which is unstable and much influenced by heat treatment. The marked influence of quenching on the properties of bronze with 10 per cent aluminum is also well shown in Fig. 13. This alloy in rolled form has about the same tenacity, elastic ratio, hardness, hardening capacity and toughness as 0.35 per cent carbon steel. Experiments by Corse and Comstock † have shown that cast rods of 10 per cent aluminum bronze quenched at 850° C. and annealed at 600° C. have an ultimate strength and elastic limit of approximately 95,000 and 45,000 lb. per sq. in, respectively, with an elongation of 10 per cent in 2 in. and a capacity to endure over 5,000,000 bending reversals producing an extreme fiber stress of 33,000 lb. per sq. in. Other tests by the Alloys Research Committee show that the 10 per cent aluminum bronze has almost constant strength for increasing temperatures up to 700° C. but the alloy is much more brittle above 400° C. than at normal temperatures.

The insertion of 1 per cent of manganese into a 10 per cent aluminum bronze increases the yield point and ductility of the alloy without producing material change in its strength or endurance under reversals of stress.‡

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* From Eighth Report of Alloys Research Com. *Proc. Inst. Mech. Engr.*, 1907. Pt. 1, p. 57.

† *Proc A. S. T. M.*, Vol. 16, p. 134.

‡ See Alloys Research Com. Ninth Report *Proc. Inst Mech. Engr.*, 1910, Pt. 1, p. 130.

Aluminum bronzes are almost incorrodible in sea water and are superior in this respect to Muntz metal or naval brass.

The modulus of elasticity for aluminum bronze is about 15,000,000 lb. per sq. in.

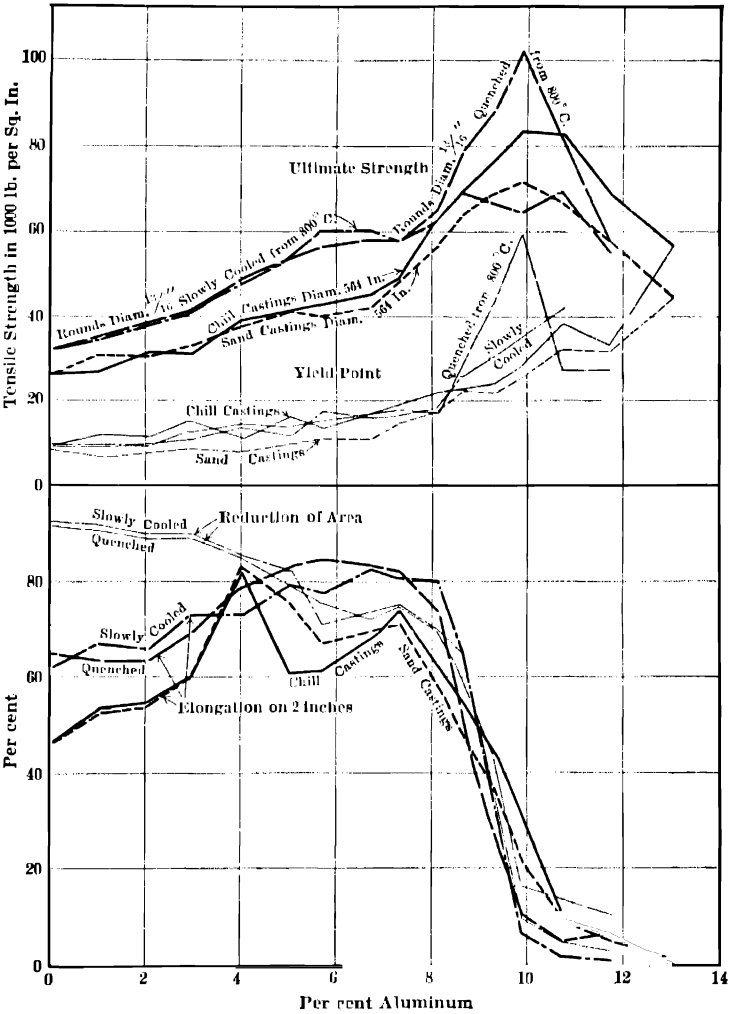


FIG. 13.—The Influence of Aluminum on the Tensile Properties of Aluminum Bronze. (Alloys Research Com., *Proc. Inst. Mech. Engr.*, 1907, pp. 113–133.)

801. Aluminum-copper Alloys.—By the addition of a small proportion of copper, generally less than 5 per cent, to "pure" aluminum, it is possible to secure a metal which is less liable to burning and to produce light castings that are stronger, harder and tougher than those made from aluminum.

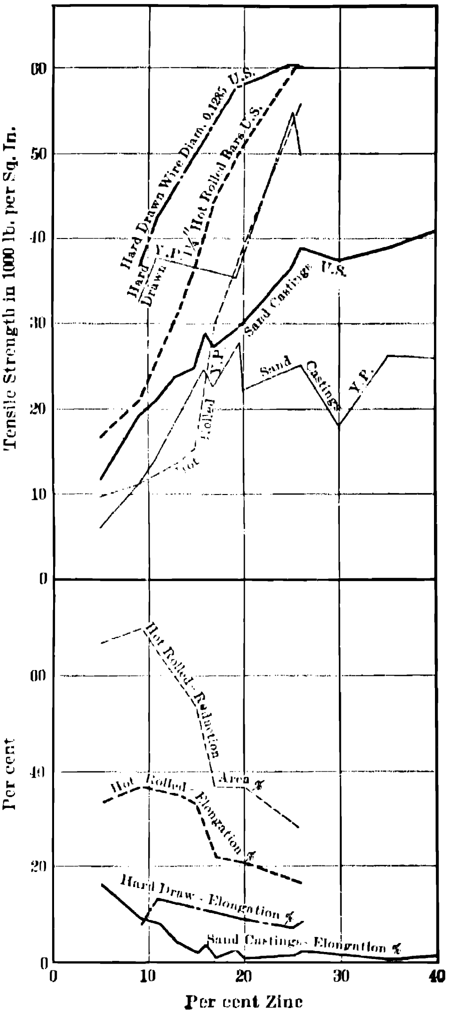
Some of the mechanical properties of these alloys are listed in Table 3. They do not possess as high resistance to corrosion in sea water as the aluminum bronzes, nor are they as satisfactory as " pure " aluminum for cooking utensils. As mentioned before these alloys are much used in the automobile industry.

TABLE 3.—TENSILE PROPERTIES OF ALUMINUM COPPER ALLOYS

(From Alloys Research Com., 8th Report)

Per cent Copper.	Condition.	Diameter of Specimen. In.	Ultimate Strength. Lb. per sq. in.	Yield Point. Lb. per sq. in.	Per cent Elongation on 2 in. Per cent.
0.0	Sand cast. Slowly cooled.	0.564	10,250	4,256	19.0
1.90		....	10,400	7,390	6.0
3.76		....	16,840	10,960	4.0
4.97		....	17,560	12,310	4.0
0.00	Sand cast. Quenched from 450° C. in water	0.564	11,300	5,375	22.0
1.90		....	11,210	8,060	7.0
3.76		....	15,790	12,760	4.0
4.97		....	16,360	13,880	4.0
0.00	Hot rolled from 3 in. to $1\frac{1}{4}$-rounds.	1.250	14,550	9,850	35.5
1.90		....	24,400	14,320	27.5
3.76		....	37,700	20,300	20.0
4.97		....	32,850	19,920	19.5
0.00	Cold drawn.	$\frac{13}{16}$	19,460	19,030	19.5
1.90		$\frac{13}{16}$	33,600	31,370	13.0
3.76		$\frac{29}{32}$	44,800	41,450	7.5
4.97		$1\frac{1}{16}$	39,700	35,600	6.0
0.00	$1\frac{1}{4}$-in. rounds. Annealed and drawn with annealing to $\frac{13}{16}$ in.	$\frac{13}{16}$	16,600	15,660	23.0
1.90		$\frac{13}{16}$	30,900	28,900	16.5
3.76		$\frac{13}{16}$	37,850	34,700	8.0

✓**802. Aluminum-zinc alloys** containing less than 25 per cent of zinc are of the most commercial importance of the alloys of this group. As a class all of these alloys are very sensitive to high temperatures in melting and in solid form exhibit low strength and brittleness when heated above 50° C. Those having less than 15 per cent zinc are much used in constructions where a light, sound casting, which can be easily machined or forged into proper form, is desired. Alloys containing from 15 to 25 per cent of zinc are harder, stronger, but less ductile and more difficult to roll or draw. The alloys of high zinc content appear to suffer a decrease in strength when excessively worked either hot or cold. For example, the strength of alloys containing 26 per cent of zinc decreased when the bars were hot-rolled or cold-drawn below 1¼ in. in diameter.* The tensile properties of these alloys are indicated in Fig. 14. Unlike most of the minor metals and their alloys the aluminum-zinc alloys have well-defined yield points characterized by dropping of the scale beam during test. The modulus of elasticity for all of the light alloys is approximately 9,000,000 lb. per sq. in.



Fɪɢ. 11.—The Effect of Zinc on the Tensile Properties of Aluminum Zinc Alloys. (Alloys Research Com., *Proc. Inst. Mech. Engr.*, 1912, p. 449, 472, 494.)

Aluminum and zinc alloys containing about 5 per cent of aluminum are added in small percentages to the zinc baths used in galvanizing in order to render them more fluid.

803. Aluminum - magnesium alloys (*magnalium*) containing small percentages of magnesium, have been widely used as deoxidizers in copper smelting operations. The alloy containing 6 per cent magnesium has very good mechanical properties and is somewhat lighter than pure aluminum. It is easy to work, exceptionally strong, and ductile. Schirmeister † reports a tenacity of 42,000 lb. per sq. in., an elongation of 21 per cent and a Brinell hardness of 69 for this alloy rolled at 450° C.

Duralumin is another light alloy of aluminum with 3 to 5 per cent of copper and smaller amounts of magnesium and manganese. When rolled and heat treated its tensile strength exceeds 50,000 and its yield point 30,000 lb. per sq. in. The elongation in 2 in. is about 20 per cent. Besides use in airplane parts it is being fabricated into structural shapes for many types of construction. For more data on these alloys, see Art. 905.

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* Tenth Report Alloys Research Com., *Proc. Inst. Mech. Engr.*, 1912, Pt. 1, p. 331

† *Stahl u. Eisen*, June 24, 1915.

ALLOYS OF LEAD, TIN AND ANTIMONY

804. Lead-tin alloys are principally used in making solder, pewter and toys. These alloys have rather low melting-points, that of the eutectic containing 37 per cent lead being only 183° C. By adding tin to lead the strength and hardness are considerably increased. Furthermore, the alloys carrying more than 50 per cent lead remain pasty over a considerable range of temperature before completely solidifying. The latter property renders these alloys of value for plumbers' solder which ordinarily contains from 2 parts lead and 1 part tin to equal parts of each. For soldering tin, the alloy containing 2 parts tin and 1 part lead is much used, whereas for electrical work the best solders carry less than 10 per cent lead.

805. Lead-antimony alloys.—Antimony, like tin, serves as a hardener when added to lead but the useful binary alloys of these two metals cover only a limited range in constitution. The more useful of these alloys contain from 10 to 25 per cent of antimony. The alloys richer in lead than the above are very soft; those richer in antimony are too brittle and hard to be of value for most purposes. Alloys containing over 13 per cent antimony consist of a comparatively soft eutectic in which are embedded hard cubical crystals of antimony. In bearing metals the presence of a limited mount of these hard crystals increases resistance to wear, but a large proportion causes the bearing to heat. The softer eutectic, on the other hand, readily adjusts itself to inequalities in pressure and, wearing more rapidly than the antimony, allows space for the lubricant. Alloys containing 12 to 17 per cent antimony are inexpensive and are used to some extent for bearings carrying light loads. For properties of some bearing metals of this class, see Table 4.

Shot and bullets are made from lead containing a small proportion of antimony to increase the hardness.

806. Lead-antimony-tin alloys are of great value for type metal. A satisfactory type metal must take a full sharp impression of the mold and be sufficiently rigid to withstand press action. The alloys of lead and antimony containing over 15 per cent antimony satisfy the former requirement since they expand slightly on heating but they require a little tin to increase their compressive strength and render them less brittle. The range in composition for these alloys varies from 2 parts lead, 1 part antimony and 1 part tin to 7 parts lead, 2 parts antimony and 1 part tin. Linotype and monotype machines use cheaper alloys containing 12 to 18 per cent antimony, 3 to 8 per cent of tin, and the remainder lead.

Alloys containing 10 to 20 per cent antimony, 5 to 20 per cent tin and the remainder lead may also be used for bearings subjected to moderate loads (Table 4). Magnolia metal containing approximately 78 per cent lead, 16 per cent antimony and 6 per cent tin is one of the common bearing metals of this class. The range in pouring temperatures for these alloys is, however, more limited than for the equally serviceable but somewhat more expensive bearing metals consisting principally of tin.

TABLE 4.—SHOWING PHYSICAL PROPERTIES OF WHITE METAL BEARING ALLOYS

(From Rept. of Com. B-2, *Proc. A. S. T. M.*, Vol. 18, Pt. 1.)

Alloy No.	FORMULA.				DEFORMATION OF CYLINDER 1¼ in. Diam. by 2¼ in. High at 70° F., in.			BRINELL HARDNESS.		Melting-Point.	Complete Liquation Point.	Wt.	Proper Pouring Temperature, deg. Fahr.
	Copper, per cent.	Tin, per cent.	Antimony, per cent.	Lead, per cent.	At 1000 lb.	At 5000 lb.	At 10,000 lb.	At 70° F.	At 212° F.	Deg. Cent.	Deg. Cent.	Oz. per cu. in.	
1	4.5	91.0	4.5	....	0.000	0.001	0.015	28.6	12.8	225	371	4.24	824
2	3.5	89.0	7.5	....	0.0000	0.0015	0.0120	28.3	12.7	238	362	4.27	808
3	8.33⅓	83.33⅓	8.33⅓	..	0.0010	0.0045	0.0070	34.4	15.7	239	422	4.31	916
4	3.0	75.0	12.0	10.0	0.0005	0.0025	0.0090	29.6	12.8	185	291	4.35	680
5	2.0	65.0	15.0	18.0	0.0010	0.0030	0.0090	29.6	11.8	185	280	4.48	661
6	1.5	20.0	15.0	63.5	0.0015	0.0050	0.0180	24.3	11.1	185	267	5.39	638
7	...	10.0	15.0	75.0	0.0010	0.0050	0.0230	24.1	11.7	240	260	5.62	625
8	...	5.0	15.0	80.0	0.0020	0.0090	0.0620	20.9	10.3	243	260	5.80	625
9	...	5.0	10.0	85.0	0.0040	0.0120	0.0840	19.5	8.6	243	255	5.92	616
10	...	2.0	15.0	83.0	0.0010	0.0100	0.1540	17.0	8.9	245	260	5.82	625
11	...	...	15.0	85.0	0.0010	0.0100	0.1190	17.0	9.9	247	260	5.94	625
12	...	...	10.0	90.0	0.0025	0.0170	0.2850	14.3	6.4	247	265	6.17	634

✓ **807. Babbitt metals** are alloys with a tin base containing small proportions of copper and antimony. They are so called from the inventor Isaac Babbitt. Fig. 15 shows the microstructure of a babbitt metal whose

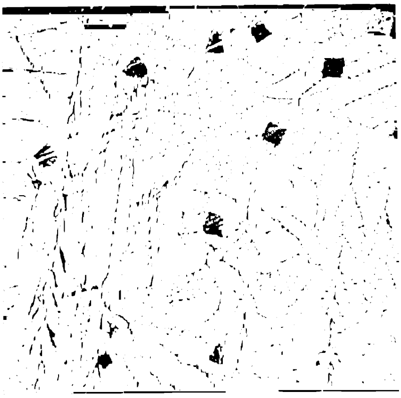

FIG. 15.—Babitt Metal Containing 89% Tin, 7% Antimony, and 4% Copper. Cubes of SbSn and white needles of ε copper-tin solid solution set in dark tin-rich metal. Etched with 5% Hydrochloric Acid in Alcohol. Magnification = 75d.

composition is very nearly that of alloy No. 2, Table 4. The white cubes are usually designated as SbSn, though as a matter of fact they are a solid solution of antimony and SbSn. The white constituent which tends to form needles and star-like figures is the ε solid solution in the copper-tin series, but in some articles is referred to as the compound CuSn. The dark metal is rich in tin and soft, while the cubes of SbSn and needles of ε solid solution are quite hard. Soft varieties of babbitt carry about 4 or 5 per cent of copper and 6 to 8 per cent of antimony, whereas the harder alloys contain 6 to 10 per cent of copper and 8 or 10 per cent of antimony. An idea of the mechanical and physical properties of the more valuable of these alloys is furnished in Table 4 abstracted from Report of Com. *B*-2 of *A. S. T. M.*, 1918. Since the rate of heating of such bearings under service conditions is dependent upon the size and distribution of the crystals of the copper-antimony compound, the temperature of pouring and rate of cooling must be carefully controlled. Rapid chilling or very slow cooling causes heating of the bearing.[*] By heating the core of the mold it is possible to secure an intermediate rate of cooling such that the crystals will be well-defined, uniformly dispersed throughout the mass and not over .01 in. in size. Such treatment leads to a more serviceable bearing.

808. Alloys of Low Fusibility.—The following remarkable alloys, all of which fuse at very low temperatures, may be used as safety-plugs in automatic fire-spraying pipe-systems in mills and for similar purposes.

TABLE 5.—FUSIBLE ALLOYS

Name.	Percentage of Ingredients.				Fusing Temperature, Deg. Cent.
	Bismuth.	Lead.	Tin.	Cadmium.	
Newton's	50	31	19	0	95
Rose's	50	28	22	0	100
Darcet's	50	25	25	0	93
Wood's	50	24	14	12	66–71
Lipowitz's	50	27	13	10	60

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[*] Behrens and Baucke, *The Metallographist*, Vol. 3.

CHAPTER XXVII

THE EFFECT OF TEMPERATURE ON THE MECHANICAL PROPERTIES OF METALS

EFFECTS ON IRON AND STEEL

809. Importance of Temperature Effects on Properties.—At the present time the ferrous metals are the principal materials for boilers, grates, fire-boxes, staybolts, engine cylinders and pistons, ladles, shafting, rails, axles, refrigerating machinery and other machine parts, which are subjected to considerable variation in temperature or to long periods at higher or low temperatures. Often the breakage of such parts would result in loss of life or large financial loss. It therefore is imperative that the properties of these metals under such conditions be well understood. We shall next consider the more important effects of temperature on the mechanical properties of iron and steel.

810. Effects on Strength.—This subject has been very fully and carefully investigated at the Watertown Arsenal, and a full series of stress diagrams, similar to that of Fig. 1, is shown in the report for 1888. The curves of Fig. 1 exhibit the action of a structural steel (0.20 per cent carbon) having a normal tensile strength at 70° F. of 70,000 lb. per square inch and an elastic limit of about 37,000 lb. per square inch. Elastic limits and ultimate strengths may be gotten from this figure. A better notion of the variation in strength of different carbon steels, wrought iron and cast iron with temperature, can be formed from Fig. 2. Study of Fig. 2 reveals that the ultimate strength of the steels and wrought iron does not vary greatly for temperatures between 0 and 300° F., there being a slight sag in strength at 200° F. As the temperature is raised above 300° F. the strength increases until a maximum 10 to 15 per cent higher than the normal strength is reached at 500° F. Further increase in temperature is accompanied by a proportionate reduction in tenacity until at 1600° F. the strength is only 15 or 20 per cent of the normal. Corroborative evidence is also furnished by the data in Figs. 4, 5, 6, and 10. For information regarding strength of alloy steels at high temperatures see Art. 815.

It is noteworthy that the tenacity of cast iron is not materially affected by variation in temperature up to 900° F. For increases in temperature above 900° F. the strength falls proportionately until at 1600° F. it is approximately 20 per cent of the normal value.

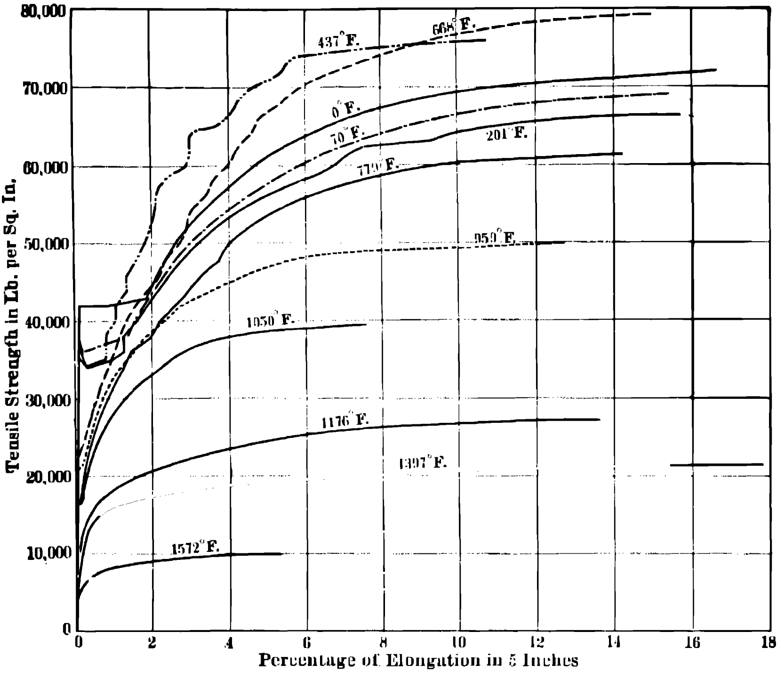

FIG. 1.—Stress-diagrams of Steel Bars at Various Temperatures. Carbon =0.20%; Manganese =0.45%. (*Tests of Metals*, 1888.)

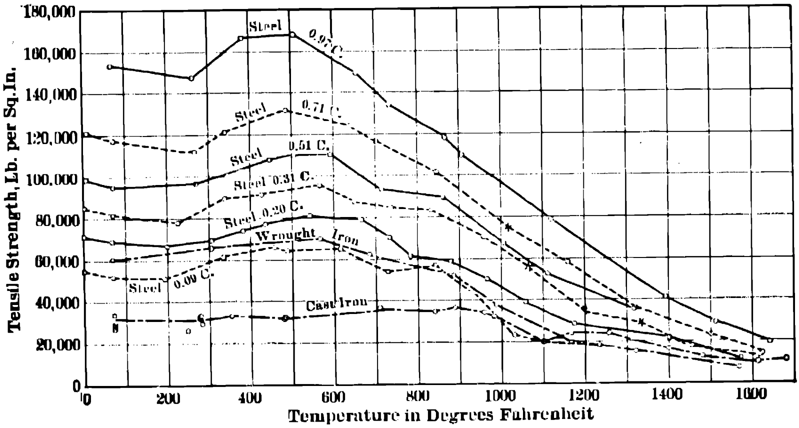

FIG. 2.—Variations in Tensile Strength of Ferrous Metals with Temperature. (*Tests of Metals*, 1888.)

The " creep " or " flow " of steel when subjected to ordinary working stresses at high temperatures * must be properly evaluated in designing high-pressure steam lines, oil refineries, and other similarly exposed equipment. Kanter and Spring, *Proc. A.S.T.M.*, Vol. 28, Pt. 2, p. 80, have made a valuable contribution on flow in carbon cast steel (C. = 0.20 − 0.40 per cent). Fig. 3 is taken from their paper. Since failure of such steels under flow is accompanied by considerable elongation, they argue that a flow of one per cent in many classes of service, like high-pressure steam lines, will do little or no harm. Hence they have developed from their data the curves of Fig. 3. It is of interest to note (Fig. 3) that the proportional limit determined in a short time test at a given temperature coincides quite closely with one per cent flow in one year for temperatures less than 850° F. and with one per cent flow for 1000 hours for temperatures between 900 and 1200° F. The low value of stress at which one per cent flow occurs in a year is noteworthy. High-speed steels, see Table 2, and stainless steels, Art. 903, withstand higher stresses than carbon steels for the same flow or creep.

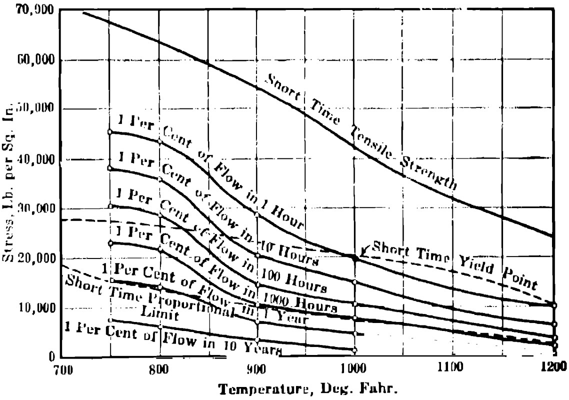

Fig. 3.—Flow in Cast Carbon Steels (Kanter and Spring).

Steel or wrought iron exposed to low temperatures has higher static strength but less ductility than at room temperatures. At the temperature of liquid air (−220° F.) a medium carbon steel bar tested at the Watertown Arsenal exhibited an increase of 51 per cent in elastic limit, 35 per cent in ultimate strength, but a reduction of 63 per cent in elongation from the corresponding room-temperature properties.

811. Importance of Effect on Elastic Limit.—In Fig. 4 combined curves for carbon steels showing mean variations in mechanical properties with temperature indicate that whereas the mean ultimate strength varies less than 15 per cent from the normal for temperature variations between 0 and 700° F., the mean elastic limit decreases in direct proportion to the increase in temperature above 0° F. Therefore the ratio of the elastic limit to the ultimate strength—the elastic ratio—is much less at high temperatures than at ordinary temperatures. For 100° F. the mean value of the elastic ratio is 0.57, while at 500° F. it is only 0.36. Figs. 1, 3, and 5, showing results of tests on individual classes of steel, substantiate the above statements.

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* For bibliography and much data see *Proc. A.S.T.M.*, Vol. 24, Pt. II, p. 9.

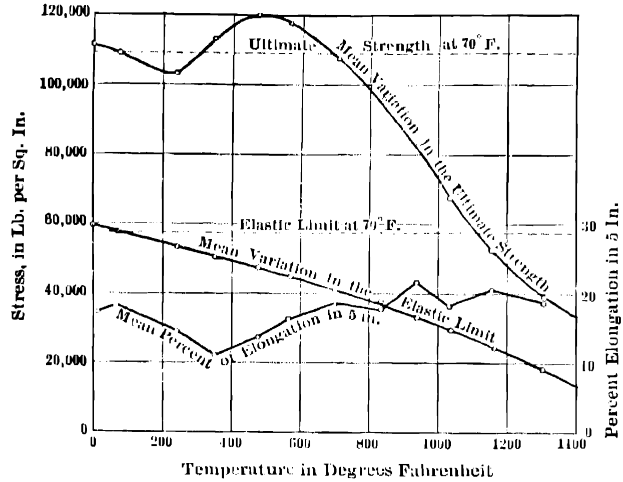

Fig. 4.—Grand Mean Curves from Temperature Tests on Steel Rods.

Diameter of rods, 1¼ in., of specimen 0.8 in. Ten degrees of hardness, from 0.09 to 0.97% C. (*Tests of Metals*, 1888, p. 245.)

For structural purposes, therefore, the working strength of wrought iron and steel must be regarded as regularly diminishing, while the temperature increases, the rate of diminution being about 4 per cent per 100° *F. increase in temperature.*

812. The Change in Ductility.—Steel and wrought iron both exhibit a marked reduction in per cent elongation for temperatures in the vicinity

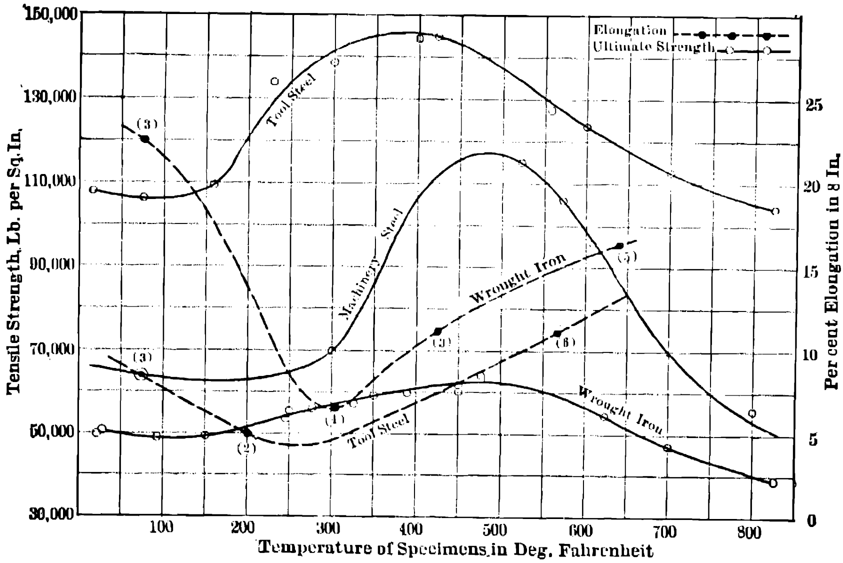

Fig. 5.—Variations in Strength and Ductility of Wrought Iron and Steel at Different Temperatures. (From Cornell University Tests in *Jour. West. Soc. Engr.*, Vol. 1.)

of 300° F., as the curves of Fig. 5 show. At this temperature **wrought iron and soft steel have elongations of approximately one-third to one-half** of the respective values at normal temperatures. The reduction in elongation at this temperature for high carbon steels is not quite so marked.

Minimum values for the per cent reduction in area of wrought iron and steel occur at somewhat higher temperatures, generally between 400 and 500° F., as indicated in Fig. 6.

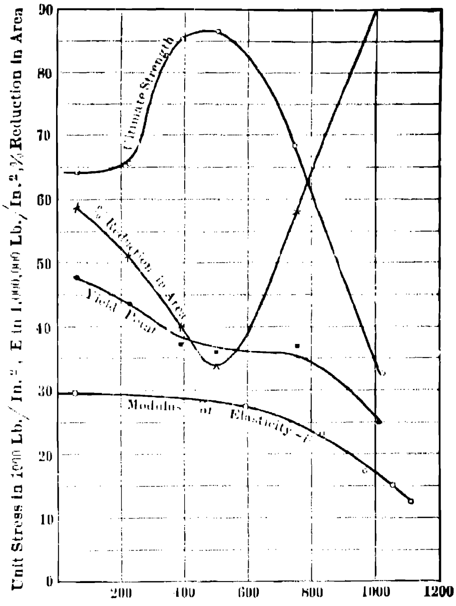

FIG. 6.—The Effects of Variations in Temperature on the Elasticity and Strength of Mild Steel.

(Lea and Crowther, *Engineering*, Vol. 98, p. 488.)

813. The Change in the Modulus of Elasticity.—The results plotted in Fig. 6 and 7 show that the modulus of elasticity of wrought iron and of steel decreases as the temperature increases. This decrease amounts to approximately 2 per cent per 100° F. increase of temperature up to 500° F. For higher temperatures the reduction in stiffness is more marked, being about 20 per cent at 800° F. and 55 per cent at 1100° F.

814. Effect on Resistance to Impact.—The variation in the resistance to a single blow of eight varieties steel tested at different temperatures is well shown in Fig. 8. The composition of these steels is given in Table 1.

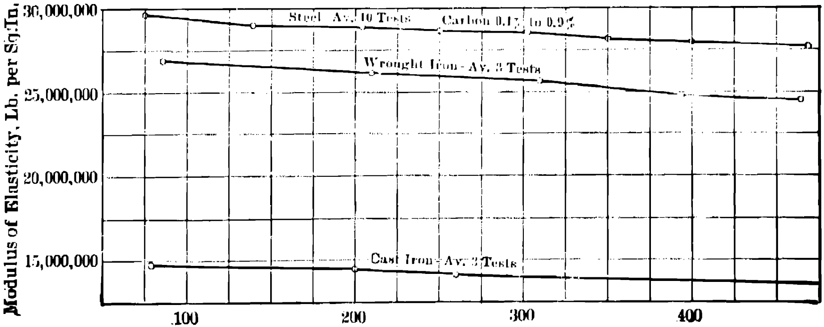

FIG. 7.—Effects of Moderate Variations in Temperature on the Modulus of Elasticity of Iron and Steel. (*Tests of Metals*, 1887.)

Each curve represents tests on 50 to 60 specimens. Each 0.4×0.4×2.4-in. test-piece was made with a milled notch 0.08 in. wide and 0.08 in. deep, the notch being provided with a round bottom. Specimens were broken in a Guillery * machine over a 1.6-in. span and under an initial energy of 5210 in. lb. The tests show that the resistance of these steels increased slightly as the temperature rose from room temperature to a value between 250° and 400° F. The resistance to a single shock then diminished with increasing temperatures until a minimum resistance was reached at a temperature in the vicinity of 900° F., and that with further increase in temperature the resistance again rose.

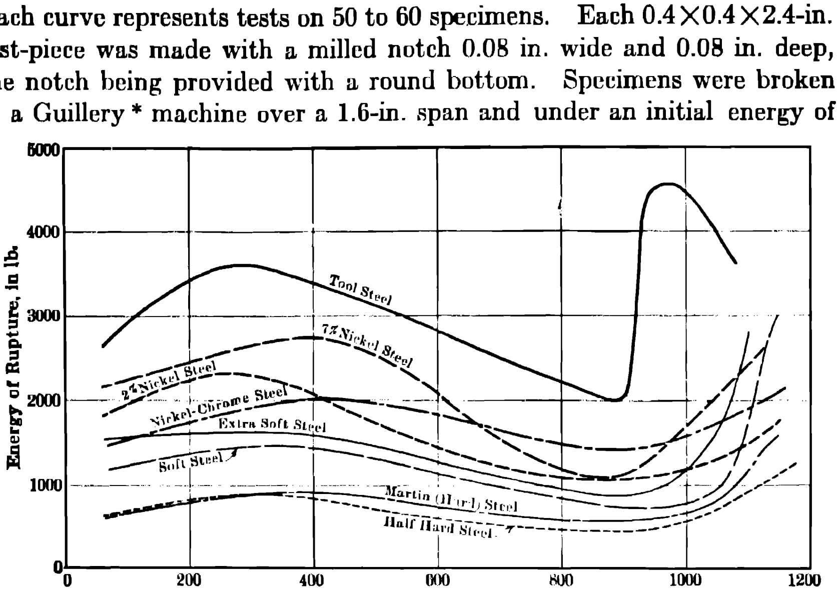

FIG. 8.—Effects of Temperature on the Resistance of Various Annealed Steels to Impact. (Guillet and Révillon in *Proc. I. A. T. M.*, 5th Congress, III₄.)

TABLE I.—COMPOSITION OF STEELS SUBJECTED TO IMPACT AT VARIOUS TEMPERATURES. (GUILLET and RÉVILLON)

Steel	Per Cent of					Annealing Treatment in Air at (° C.)
	C	Si	Mn	S	P	
Extra soft	0.218	0.26	0.24	0.041	0.013	850
Soft	0.345	0.20	0.51	0.048	0.068	800
Half hard	0.491	0.44	0.34	0.044	0.062	800
Martin (hard)	0.725	0.40	0.33	0.025	0.013	750
Tool	1.224	0.05	0.04	0.040	0.023	Plane bars at 700°
2 per cent Ni	0.085	0.01	0.15	0.017	Ni=2.99	850
7 per cent Ni	0.162	0.18	0.20	Ni=7.10	....	600
Nickel-chrome	0.105	0.11	0.34	Ni=4.38	Cr=0.85	750

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* This machine is provided with a fly wheel to which is attached a knife for breaking the specimens. The energy absorbed in breaking the test piece is measured by the diminution caused in the speed of the fly wheel.

Tests have demonstrated that repeated blows or working at temperatures between 500° and 600° F. (a blue heat) greatly impair the ductility and toughness of wrought iron and structural steel. Experiments by C. E. Stromeyer* showed that the structural steel and wrought-iron bars, which in normal condition could be bent cold through an angle of 45° first on one side of axis of the test-piece and then on the other for 12 to 26 bends, stood only 1½ to 3 bends at a blue heat. Tension tests by R. Krohn † on wrought iron, soft steel, and medium steel showed that the decrease in energy of rupture due to working at a blue heat was 56, 30.4, and 26 per cent, respectively, while the elongation decreased 53, 31 and 28 per cent, respectively.

In certain experiments by T. Andrews ‡ wrought-iron car axles heated to various temperatures suffered impact from a 2240-lb. tup dropping through a distance of 30 in.; they were then turned over, the temperature restored and the blow repeated. Although the material itself was very non-uniform the results plotted in Fig. 9 demonstrate that the resistance was a minimum when the axles were tested at 570° F., a blue heat. Fig. 9 also shows the necessity of making impact tests at the same temperature if the results of different tests are to be compared.

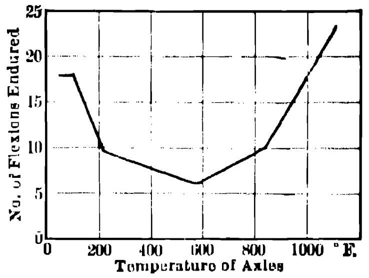

Fig. 9.—Effects of Temperature on the Endurance of Wrought Iron Railway Axles to Alternate Bending under Impact. (T. Andrews.)

Although comparatively few impact tests have been made at low temperatures, the available information indicates that the resistance to shock diminishes as the temperature drops below room temperature. Andrews found in other tests § on wrought-iron axles that the number of blows required to produce rupture at 100° F. was 50 per cent greater than at 0° F. Axles broken at −18° F. exhibited a crystalline fracture perpendicular to the axis of the piece; those broken at 300° F. showed a fibrous uneven fracture.

Impact tests by Goerens and Hartel || on mild steel show a great increase in brittleness over the results at normal temperatures when the specimens were broken at −103° F. and below.

The bar (Art. 810) tested under tension at the temperature of liquid air required approximately one-half as much energy to rupture it as at

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* *Proc. Inst. of Civ. Engr.*, Vol. 84, p. 114.

† Reported by G. Henning in *Engr. News*, Vol. 27, p. 42.

‡ In a Bessemer Premium Paper before the *Soc. Engr.* (London), 1896.

§ *Proc. Inst. Civ. Engr.*, Vol. 94, p. 209.

|| *Zeitschrift für anorganische Chemie*, Vol. 81, p. 130.

normal temperature, thus showing its increased fragility at low temperatures.

815. Effect on Hardness.—An elaborate series of tests by F. Robin (reported in *Rev. de Métal.*, Vol. 5, p. 893; Vol. 6, p. 180) in which the Brinell method was used, show that the curves between hardness and temperature are of of the same general character as the curves between tensile strength and temperature.

TABLE 2.—BRINELL HARDNESS OF SPECIAL ALLOY STEELS AT VARIOUS TEMPERATURES. (ROBIN)

ALL STEELS TESTED AS RECEIVED EXCEPT AS NOTED

Kind of Steel.	Hardness at				Composition in %				
	−50 −58	100 212	400 752	600° C. 1112° F.	C.	Cr.	W.	Co.	Va.
High speed	...	655	515	480	.65	6.06	18.5	6.0	.....
High speed	...	540	465	400	.50	3.20	14.0	5.0	.....
High speed	...	415	350	315	1.00	8.00	20.8	Mo.	.....
Molybdenum (*N*)	385	375	345	295	.30	....	.....	2.0	.....
Molybdenum (*H*)	...	640	430	290	.30	....	.....	2.0	.....
Molybdenum	315	300	290	225	.30	....	.....	0.5	.....
Vanadium (*N*)	355	340	300	170	.80	....	.....	......	0.7
Vanadium (*H*)	...	545	340	180	.80	....	.....	......	0.7
Tungsten (*N*)	...	355	345	250*	1.2	....	6.0	Ni.	.....
Tungsten (*H*)	...	625	445	250	1.2	....	6.0	......	.....
Nickel	...	335	250	160	....	....	.....	16.0	.....
Nickel	....	165	135	80†	....	....	.....	27.0	.....
Chrome (*N*)	...	350	320	230	1.18	1.37	.....	......	.....
Chrome (*H*)	...	660	415	160	1.18	1.37	.....	......	.....
	50° C.	250° C.	400° C.	600° C	C.	Mn.	Si.	P.	S.
[1] Carbon (*N*)	290	320	285	180	2.02	.28	.25	.013	.017
[1] Carbon (*H*)	350	400	325	...	2.02	.28	.25	.013	.017
[2] Carbon (*N*)	265	280	245	160	1.08	.30	.12	.012	.020
[2] Carbon (*H*)	600	520	325	110	1.08	.30	.12	.012	.020
[3] Carbon (*N*)	205	240	225	...	.60	.72	.11	.022	.018
[3] Carbon (*H*)	630	560	355	120	.70	.53	.34	.077	.053
Wrought iron	105	155	125	35	.04	.14	.11	.018	.020

N = as received. *H* = hardened. * Estimated. † At 900° C. [1] Hardened in water at 1150° C., austenitic. [2] Hardened at 820° C. [3] Hardened at 850° C., martensitic.

Table 2 summarizes the more important results of Robin's work. The high, uniform hardness exhibited by the high-speed steels and by the molybdenum and tungsten steels at temperatures up to 1100° F. is in marked contrast to the hardness of the hardened carbon steels which were materially softened at 700° F. The high hardness of the 27 per cent nickel steel at 900° C. (1652° F.) is also noteworthy. Since certain comparisons by Robin indicate that the hardness is proportional to the strength for temperatures up to 400° C. (752° F.), this series of experiments furnishes important information concerning the relative strength of alloy and ordinary

816. Effect on Specific Gravity.—Tests by Langley * show that specific gravity of steel increases from 7.76 at white heat to 7.83 as the temperature falls to a black heat.

EFFECT ON ALLOYS AND METALS MUCH USED IN MACHINE PARTS

817. Description of Tests.—Owing to the extensive use of brasses, bronzes and other alloys in valves, shafting, parts of pumps and engines often subjected to temperatures from 400 to 700° F., a knowledge of the effects of such temperatures upon the mechanical properties of these metals is also essential if safe and economical designs of such parts are to be made. One of the most extensive series of tests thus far made on the effects of high temperatures on the mechanical properties of alloys was reported by Bregowsky and Spring to the Sixth Congress of the I.A.T.M.† We shall now present the main results of these investigators. Their experiments included both tensile and torsion tests. Round bars with the gauged portion turned down to a constant diameter of 0.65 to 0.85 in., depending on the size of bar as received, were used. The gauged length of the tension specimens was 2 in.; of the torsion test-pieces, 8 in. All metal was obtained from commercial foundries and all specimens for a given series of tests were from the same heat. Temperatures were secured through resistance coils which were placed around the specimens, due care being taken to insulate the specimen and to reduce the heating effect due to magnetic induction to a minimum. Each point on the diagrams represents from 2 to 10 results. In the tension tests the yield point was gotten by dividers; in the torsion tests a troptometer was used to measure detrusions. The compositions of the various metals tested may be found in Table 3.

818. Effect on Tensile Properties of Alloys.—Fig. 10 shows the effects of variations in temperature from room temperature to 1000° F. on 16 commercial alloys. It should be noted that both the ultimate strength and yield point of the copper-tin bronzes and the aluminum bronzes remain fairly constant for temperatures between 70° and 400° F. For increasing temperature both of these stresses decrease. The brasses, manganese bronze, and Monel metal exhibit a considerable falling off in strength as the temperature is raised above 70° F. It should also be noted that with the exception of manganese bronze and Monel metal the ductility of the brasses and bronzes is very little at temperatures above 600° F. The high strength and ductility exhibited by the rolled Monel metal at all temperatures is remarkable.

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* *Am. Chem.*, 1876.

† A good bibliography on this subject may be found in the *Proc. of the Fifth Congress of the I.A.T.M.*, entitled "The Influence of Increased Temperatures on the Mechanical Qualities of Metals," by M. Rudeloff.

TABLE 3.—CHEMICAL ANALYSES OF ALLOYS AND METALS USED IN TESTS AT VARIOUS TEMPERATURES. (BREGOWSKY and SPRING)

Material.		Composition in Per Cent.						
Mark.	Name.	Cu	Sn	Zn	Pb	Fe	Al	P
	Alloys used in Tensile Tests.							
1	**Copper-tin bronze (3)**	87.02	12.46	0.20	0.06	0.30		
2	**Copper-tin bronze**	89.50	10.22	0.00	tr.	0.38	...	0.035
3	**Brass**	86.19	5.69	5.03	3.02	0.20		
4	**Aluminum bronze**	94.94	0.03	....	0.16	0.14	4.90	———
5	**Aluminum bronze**	88.86	0.48	0.15	0.17	0.75	9.67	Mn
6	**Cast manganese bronze**	58.10	0.51	39.05	tr.	2.21	———	0.055
7	**U. S. Navy brass S-C**	80.32	3.98	12.80	2.78	0.24	C	
8	**U. S. Navy bronze M(2)**	86.92	7.72	3.62	1.22	0.23		
9	**U. S. Navy gun bronze G**	87.60	10.40	1.31	0.39	0.11		
10	**Cast Monel metal**	27.11	0.08	64.79	0.13	5.46	0.32	2.33
16	**Rolled rod brass**	62.30	0.00	34.84	2.53	0.15		
18	**Rolled Monel metal**	27.22	....	....	(Ni 68.64)	2.38	0.225	1.56
	Alloys used in Torsion Tests.							
							Al	
L	**Parsons' manganese bronze**	59.58	0.64	38.08	0.00	1.22	0.34	Ni
G	**1½ in. rolled Monel metal**	27.08	(C 0.186)	(Mn 1.52)	0.28	2.50	...	68.40
H	**Rod brass**	61.08	0.18	35.72	2.34	0.42	...	P
I	**Tobin bronze**	59.86	0.80	38.94	0.00	0.46	...	0.0015
J	**Elephant (phosphor) bronze**	95.52	3.87	0.0	0.00	0.16	...	0.307
K	**Delta-metal**	56.56	0.76	39.36	0.56	2.40	...	0.004

Material.		Composition in Per Cent.						
Mark.	Name.	C	G C	C C	Si	Mn	S	P
	Ferrous Metals used in Tensile Tests.							
11	**Soft cast-iron (3)**	...	3.37	0.17	2.57	0.60	0.103	0.73
14	**Cast steel (2)**	0.302	———	....	0.22	0.61	0.068	0.045
15	**Cold-rolled shafting**	0.140	Ni	....	0.031	0.80	0.108	0.079
17	**30% nickel-steel, rolled**	0.285	30.92	....	0.14	2.80	0.017	0.011
	Ferrous Metals used in Torsion Tests.							
A	**Cold-rolled shafting**	0.093	....	Va	0.011	0.73	0.117	0.198
B	**Cumberland C. R. shafting**	0.083	....	....	0.024	0.50	0.110	0.101
C	**O. H. Machinery steel**	0.084	....	....	0.024	0.49	0.029	0.013
D	**3½% nickel vanadium steel**	0.365	3.25	0.45	0.132	0.45	0.042	0.032
E	**25% nickel-steel**	0.186	25.03					
F	**30% nickel-steel**	0.275	30.92	....	0.140	2.80	0.017	0.011
P	**35% C. cumberland C. R.**	0.375	Cr	....	0.120	0.51	0.50	0.013
N	**Vanadium Tool Steel**	0.722	0.49	0.145	0.160	0.32	0.034	0.014

The behavior of the cold-rolled shafting and the cast steel is in accordance with the data of Art. 810 and 812. The 30 per cent nickel steel shows similar changes in strength properties but exhibits much higher ductility at temperatures under 600° F. than either of the other steels.

819. Effect on Torsional Properties.—Data on the strength and angle of twist under torsion is given for 15 metals in Fig. 11. With the exception of the carbon steels, all of the metals tested show a progressive falling off in torsional strength as the temperature is increased above 70° F. The curves for the carbon steels are somewhat similar to the tensile strength—temperature curves. In these tests also, the Monel metal shows both high-shearing strength and ability to withstand severe overstrain.

820. Effect on Modulus of Elasticity.—It is to be deplored that the effects of temperature on the stiffness of these metals was not noted. From tests made at the Berlin Testing Laboratory in 1893 it appears that the

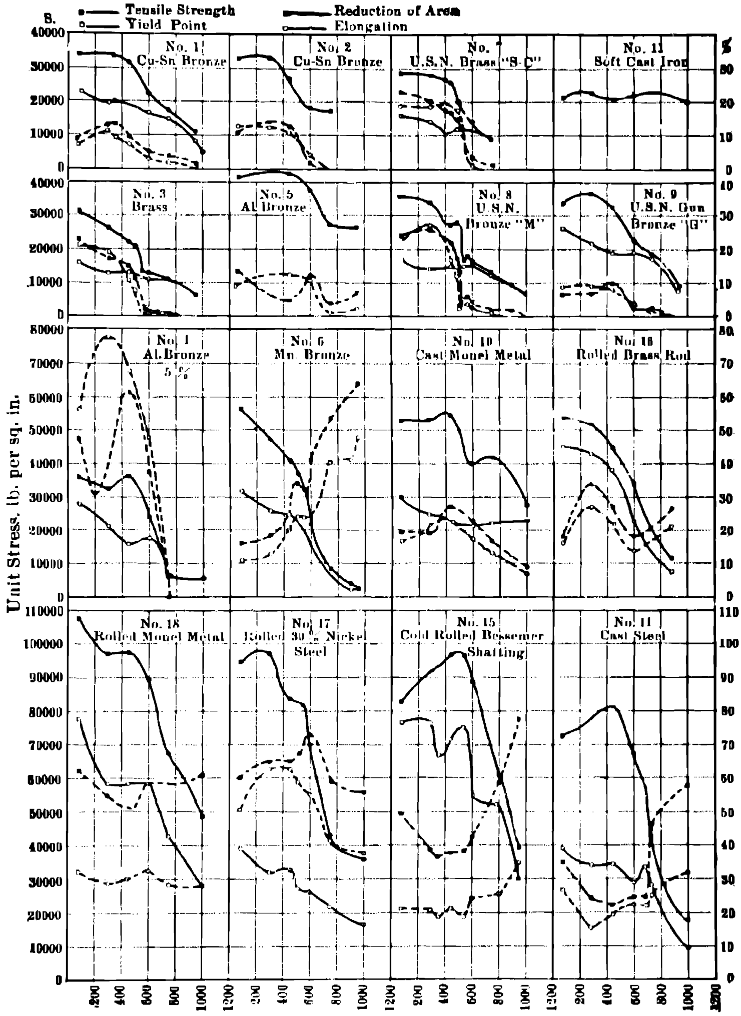

FIG. 10.—Effects of Variation in Temperature on the Tensile Properties of Different Commercial Alloys. (Bregowsky and Spring.)

modulus of elasticity copper and cast delta metal increase 10 to 15 per cent as the temperature increases from 70 to 200° F. and then fall off rapidly as the temperature is further raised, reaching room-temperature values again when the temperature reaches 400° F. Rolled delta metal exhibited more pronounced diminution of stiffness with increase in temperature than did the cast delta metal. A 4 per cent manganese bronze had as high modulus at 600° F. as at 70° F.

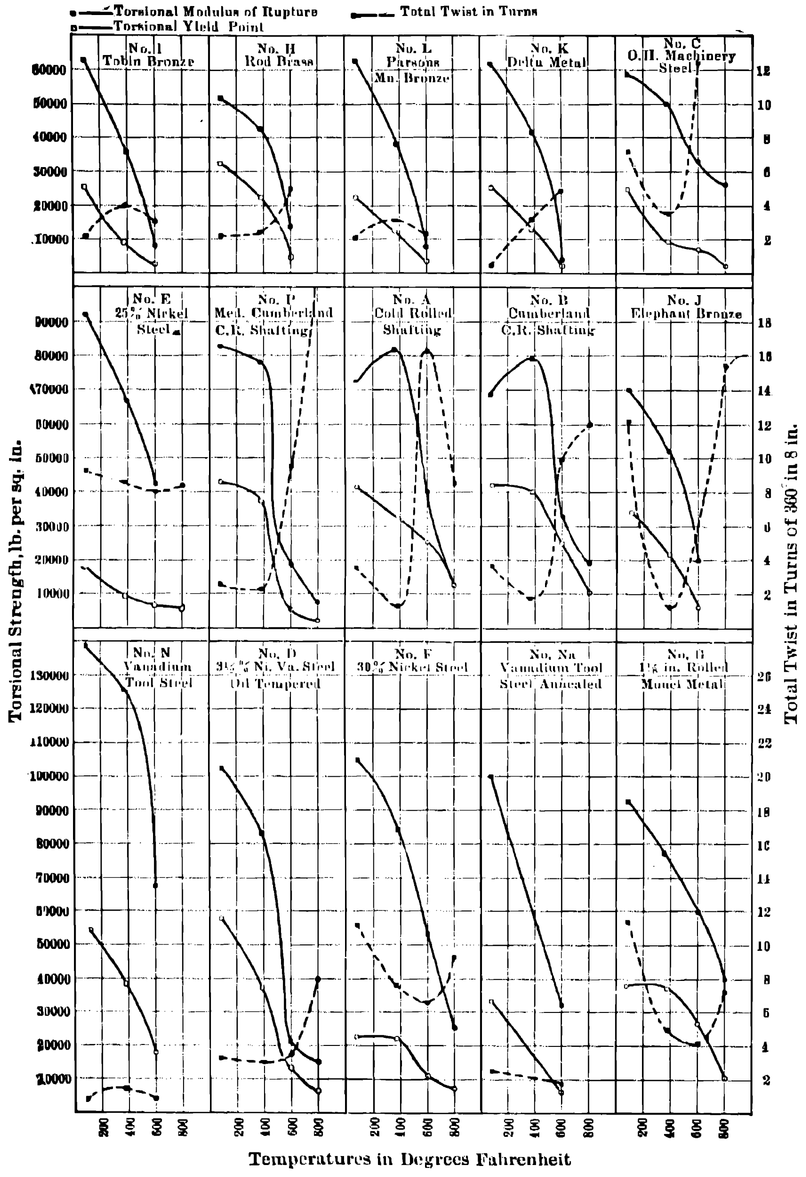

FIG. 11.—Effects of Variation in Temperature on the Torsional Strength and Angle of Twist of Commercial Rolled Alloys. (Bregowsky and Spring.)

CHAPTER XXVIII

FATIGUE OF METALS

BY J. B. KOMMERS *

821. Fatigue Defined.—Experiments have shown that metals will fail when loads are repeated thousands or millions of times, not only at unit stresses less than the ultimate, but often at unit stresses less than the elastic limit. This type of rupture has been called *fatigue* failure. Although there is no generally accepted explanation of the mechanism of fatigue of metals, Gough † has shown that for ductile materials failure is initiated by the maximum component of shear stress on the planes of "easy glide" in the crystals of the metal. Rupture is started by localized deformation which develops into a crack that spreads to failure.

Repeated stresses may be completely reversed, as in a rotating beam; they may be partially reversed, as for an axial tension reversed to a smaller axial compression; or they may alternate between an upper and lower limit of tension, compression, or shear. In a rotating beam test one "cycle" of stress occurs during each revolution of the specimen, as the unit stress on the outer fiber passes through a maximum compressive stress and then a maximum tensile stress.

822. "Crystallization" of Iron and Steel.—Since fractures due to fatigue often show a decided crystalline appearance, the erroneous idea has arisen that the repeated stresses caused the crystallization. The fallacy is demonstrated thus: Take a bar which has failed with crystalline fracture in fatigue, groove it, and break with a single blow. A crystalline fracture will again be revealed, showing that such structure is inherent in the bar.

823. Experiments on Fatigue.—In 1864 Sir W. Fairbairn published some results on a riveted wrought-iron girder subjected to repeated stresses and included earlier experiments by Captains James and Gaston. Fairbairn concluded from his experiments that it was not safe to use a repeated stress which was more than one-third of the ultimate strength.

In 1870 Wöhler published the results of a very exhaustive set of experiments which included repeated torsion, bending, and direct stress. The important conclusions drawn from Wöhler's experiments are:

1. Wrought iron and steel will rupture at a unit stress much below the

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* Professor of Mechanics in the University of Wisconsin.

† *Proc. A.S.T.M.*, Vol. 33, 1933, p. 3.

ultimate strength and even below the elastic limit, if repeated a sufficient number of times.

2. Within certain limits, the range of unit stress, not the maximum stress, determines the number of repetitions for rupture. (By range of unit stress is meant the algebraic difference between the maximum and minimum unit stresses applied.)

3. As the range is diminished, for a given maximum or minimum unit stress, the repetitions for rupture increase.

4. For a given maximum or minimum unit stress there appears to be a limiting range for which repetitions for rupture become infinite.

5. As the maximum unit stress increases the limiting range of stress diminishes.

These results will be better understood by a consideration of Figs. 1 and 2, and of Goodman's diagram shown in Fig. 3. Figure 1 shows the relation between unit stress and repetitions for failure when the maximum stress is as indicated and the minimum stress is zero. Figure 2 shows the case of equal and opposite stress in a rotating bar. In engineering the term "endurance limit" is used to designate the maximum unit stress which a metal can withstand for an indefinitely large number of cycles of stress. In Fig. 1 the endurance limit would be less than 38,000 lb. per sq. in., and in Fig. 2 it would be about 19,000 lb. per sq. in.

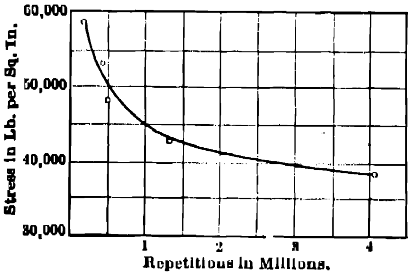


FIG. 1.

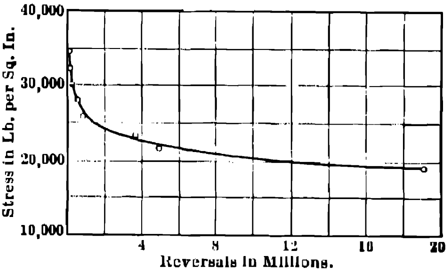


FIG. 2.

FIG. 1.—Wöhler's Fatigue Tests on Iron Axles, under repeated Bendings from Zero to the Stress Indicated.

FIG. 2.—Wöhler's Fatigue Tests on Rotating Bars, under Equal and Opposite Stresses. Range Is Twice the Stress Indicated.

In Goodman's diagram, shown in Fig. 3, the minimum values of the limiting ranges are plotted as percentages of the static ultimate strength, forming the straight line *DOB*. The maximum unit stresses are then found to fall along a line *CAB*, which intersects the line *OE* at a point which is 50 per cent of the static ultimate. The values originally plotted by Goodman were for cases in which the material had withstood over 4,000,000 cycles of repeated stress.

It is evident from this diagram that as the maximum unit stress is increased the number of repetitions before rupture can be kept very large provided the range is decreased. If the maximum unit stress is 50 per cent of the ultimate, the repetitions before rupture can be greatly increased if the minimum stress is some value greater than zero. As the maximum unit stress approaches the ultimate strength of the material, the limiting range decreases. The figure also shows that for equal and opposite stresses in tension and compression the limiting stress is 33 per cent of the ultimate.

Since Wöhler performed his experiments many other investigators have carried on researches with the object of studying the phenomena further, and of determining the effect on the repetitions for rupture of such factors as heat treatment, speed of repetition, condition of the surface of the specimen, and variation in percentages of carbon and other ingredients. The relation of limiting stress to elastic limit and ultimate strength has also been considered. For a bibliography of the work on fatigue, consult *Fatigue of Metals*, by Moore and Kommers.

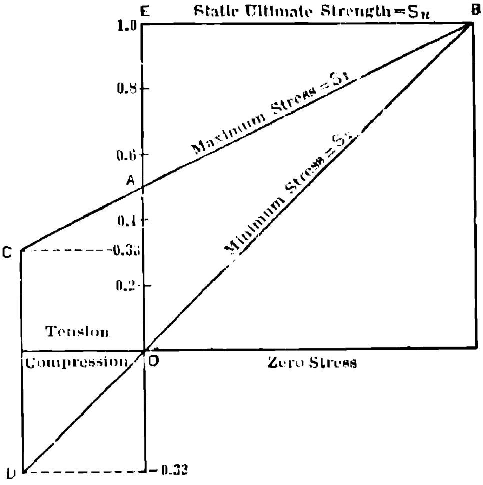
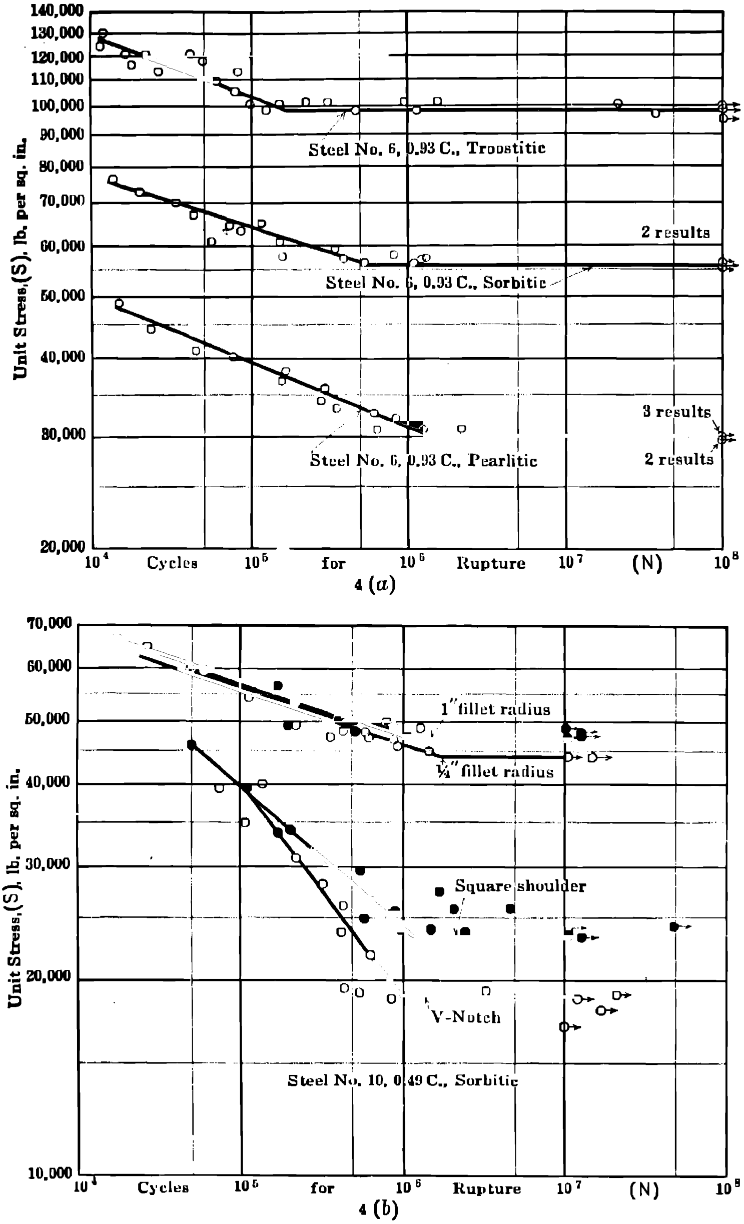


FIG. 3.—Goodman's Diagram.

In Fig. 4 are shown some characteristic "S-N diagrams" obtained from results of fatigue tests. Figure 4(*a*) indicates the effect of heat treatment of a high-carbon steel on the endurance limit, whereas Fig. 4(*b*) shows the influence of abrupt changes in cross-section on the endurance limit.

Tables 1 to 3 give static and fatigue properties of steels and nonferrous metals. For cast iron, see Art. 762.

824. Effect of Heat Treatment.—As Fig. 4(*a*) shows the fatigue strength of iron and steel is greatly influenced by heat treatment. Overheated steel is always weak, but can often be restored by reheating. Annealing in general decreases the endurance. Steel in the sorbitic condition seems to be especially resistant to fatigue. It is certain, however, that the effect of heat treatment must always depend greatly upon the previous history of the material. From the few data that are available it would seem that when metal has been subjected to repeated stresses it cannot be restored by annealing or by rest. These results are probably due to the fact that the metal had been so highly stressed or the number of repetitions so large



4 (*a*)

4 (*b*)

FIG. 4.—Typical S-N Diagram for Ferrous Metals. (From Bulletin No. 124, University of Illinois, 1920.)

that slip bands or actual microscopic fissures had been formed which were not healed by annealing.

TABLE 1.—STATIC AND FATIGUE PROPERTIES OF PLAIN CARBON STEELS

Material	Proportional Limit, lb./in.^{2}	Yield Point, lb./in.^{2}	Ultimate Tensile Strength, lb./in.^{2}	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Number	Endurance Limit, Rotating Beam, lb./in.^{2}	Investigator *
0.02% C, as hot-rolled Armco iron	16,100	19,000	42,400	48.3	76.2	69	26,000	M & K
0.21% C, as hot-rolled	39,900	40,500	70,700	35.3	62.9	...	33,400	M
0.42% C, annealed at 1560° F.	38,900	40,000	75,500	32.5	49.3	...	33,500	K
0.52% C, normalized at 1550° F.	45,500	47,600	98,000	24.4	41.7	193	42,000	M & K
0.80% C, annealed at 1470° F.	47,800	53,300	110,300	11.0	11.2	...	42,000	K
0.93% C, normalized and annealed	28,000	33,400	84,100	24.8	37.2	162	30,500	M & K
1.20% C, normalized at 1460° F.	58,600	60,700	116,900	7.9	11.6	224	50,000	M & K
QUENCHED AND DRAWN								
0.02% C, Armco Iron	35,000	36,300	50,000	36.3	76.0	109	33,000	M & J
0.37% C, sorbitic	80,600	87,300	102,000	23.3	65.1	209	57,000	M & K
0.49% C, sorbitic	67,700	69,700	96,900	23.5	57.8	197	48,000	M & K
0.93% C, sorbitic	60,300	67,600	115,000	23.0	39.6	227	56,000	M & K
0.93% C, troostitic	97,200	......	188,300	9.9	29.3	380	98,000	M & K
1.02% C	109,000	......	200,400	9.3	22.5	415	105,000	M & J
1.20% C, sorbitic	120,400	130,100	179,900	9.0	15.2	369	92,000	M & K
1.20% C, sorbitic	137,500	......	220,000	0.8	2.4	444	105,000	M & J

* M & J = Moore and Jasper, M & K = Moore and Kommers, M = McAdam, K = Kommers.

TABLE 2.—STATIC AND FATIGUE PROPERTIES OF ALLOY STEELS, NOT QUENCHED

Material	Proportional Limit, lb./in.^{2}	Yield Point, lb./in.^{2}	Ultimate Tensile Strength, lb./in.^{2}	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Number	Endurance Limit, Rotating Beam, lb./in.^{2}	Investigator *
Stainless Iron	18,200	......	82,400	16.0	20.3	175	40,000	RM
Nickel Steel	69,500	70,300	113,600	22.0	43.3	...	51,000	M
Chrome-nickel Steel	55,500	56,500	117,800	20.0	44.5	...	50,000	M
Chrome-vanadium Steel	50,500	51,500	101,800	25.5	48.5	...	44,500	M
Chrome-molybdenum Steel	47,300	48,300	85,800	29.0	49.3	...	38,500	M
Chrome-molybdenum Steel	49,900	50,900	111,400	21.0	41.0	...	49,500	M
Corrosion-resistant Steel	20,000	......	63,300	40.0	72.0	...	31,000	M
Corrosion-resistant Steel	25,000	......	99,800	28.0	48.5	...	54,500	M
Corrosion-resistant Steel	30,000	......	123,000	21.0	27.0	...	65,500	M
QUENCHED AND DRAWN								
Nickel Steel	82,400	91,000	111,800	23.6	60.2	248	67,000	M & K
Nickel Steel	139,000	142,000	154,200	15.0	55.0	...	74,000	M
Nickel Steel	174,000	......	282,000	8.2	48.7	488	112,000	M & J
Chrome-nickel Steel	115,500	128,100	138,700	18.2	61.8	291	68,000	M & K
Chrome-nickel Steel	127,500	128,000	164,500	14.5	52.5	...	84,500	M
Chrome-vanadium Steel	164,400	165,000	201,000	13.3	53.5	...	94,500	M
Chrome-molybdenum Steel	122,500	124,300	164,800	13.3	52.3	...	72,500	M
Nickel-molybdenum Steel	100,000	102,500	133,400	19.8	51.3	...	57,000	M
Cr-Ni-Mo Steel	170,000	......	312,000	11.2	26.5	530	135,000	G & M
Si-Mn Spring Steel	100,000	101,000	157,500	16.5	40.0	...	62,000	M

* RM = R. R. Moore, M = McAdam, M & K = Moore and Kommers, G & M = Gillett and Mack, M & J = Moore and Jasper.

825. Effect of Speed.—Moore and Jasper * found that at a speed of 200 cycles per minute the endurance limit was about 2 per cent lower than at 1500 cycles per minute, and that at 5000 cycles per minute the endurance limit was the same as at 1500. Hopkinson and also Jenkin have found that at very high speeds the endurance limit increases with the speed.

826. Effect of Surface Condition, Change of Section, and Size.—A flaw on the surface, a notch, or an abrupt change of cross-section causes high localized stress, and the endurance limit is thereby reduced. Figure 4(*b*) indicates that an abrupt change of cross-section may reduce the endurance limit as much as 50 to 60 per cent. Figure 5, taken from a paper by Karpov,† shows approximate curves for the reduced endurance limits which may be expected from stress concentration. Sensitivity to stress concentration increases with the tensile strength.

Size appears to influence the endurance limit only in so far as it affects homogeneity of the material. In tests made by R. E. Peterson ‡ no important size effect was found with specimens varying in diameter from 0.05 in. to 2 in., for four different carbon steels. Very small cast-iron specimens gave scattering results, but the larger specimens showed no size effect. No size effect was found by R. L. Templin for cast-aluminum alloys, nor by H. F. Moore for medium-carbon steel. Stress concentrations influence large specimens more than small specimens.

TABLE 3.—STATIC AND FATIGUE PROPERTIES OF NON-FERROUS METALS (Heavy metals above, light metals below, line.)

Material	Proportional Limit, lb./in.²	Ultimate Tensile Strength, lb./in.²	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Number	Endurance Limit, Rotating Beam, lb./in.²	Investigator[a]
Copper, annealed	3,170	32,400	56.4	71.4	47	10,000	M & J
Copper, cold drawn	38,400	56,200	6.5	52.0	104	10,000	M & J
81-19 Brass, cold drawn	21,000	76,500	16.0	64.8	. . .	23,000	M
70-30 Brass, cold rolled	. . . . .	73,200	20.0	46.3	. . .	17,500	M
95-5 Bronze, cold drawn	59,900	85,100	11.7	67.0	166	27,000	M & J
89-11 Bronze, cold rolled	38,000	82,800	37.8	63.0	. . .	27,000	M
Mn-Bronze, cast	13,000	70,000	32.8	40.8	93	17,000	RM
Nickel, cold rolled	71,600	166,200	12.2	18.8	. . .	40,000	M
Monel metal, hot rolled	49,600	89,800	40.4	69.3	166	32,000	M & J
Al-Bronze, extruded	16,900	77,500	35.5	34.0	128	34,000	RM
Aluminum, rolled	11,300	22,600	16.0	65.4	45	10,500	RM
Duralumin, rolled	25,000	51,000	16.0	50.4	100	14,000	RM
Aluminum alloy	32,000(Y.P.)	53,700	24.0	. . . .	. . .	22,800	G
Aluminum-copper alloy	19,900	59,500	24.2	37.4	. . .	15,000	M
Mg-Al alloy, extruded	13,500	39,000	15.5	30.8	58	15,000	RM
Mg-Al alloy, forged	11,400	41,300	4.0	. . . .	61	15,000	RM
Al-Mg-Si alloy	15,300	45,000	17.4	22.3	. . .	12,000	M
Mg-Cu alloy, extruded	14,300	39,000	3.0	3.6	60	11,000	RM
Electron metal	6,300	36,500	17.5	20.5	64	17,000	RM
Magnesium, extruded	1,200	32,500	6.2	4.4	41	7,800	RM

[a] M & J = Moore and Jasper, M = McAdam, RM = R. R. Moore, G = Gough.

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* *Bulletin* No. 136, University of Illinois, 1923, p. 58.

† *Modern Stress Theories* by A. V. Karpov, *Trans. A.S.C.E.*, Vol. 102, 1937, p. 1184.

‡ *Applied Mechanics*, Vol. 1, No. 2, 1933, p. 79.

827. Effect of Composition.—Results show that in normal steels the strength against fatigue increases with the carbon content up to about 0.90 per cent carbon. Heat treatment will, of course, greatly influence all results on carbon steels.

Ingredients such as nickel, chromium, and vanadium apparently increase the endurance, although this is a matter which has not been studied systematically.

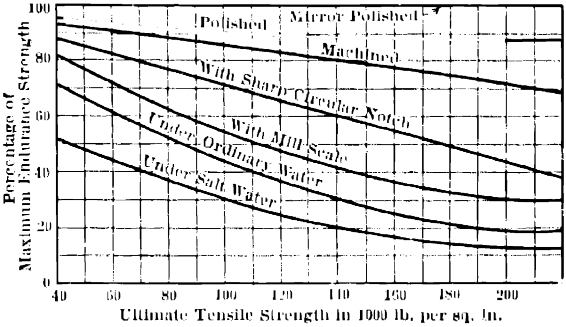

FIG. 5.—Reduction in Endurance Strength of Steel Alloys Due to Surface Conditions (A. V. Karpov).

828. Relation to Elastic Limit and Ultimate.—Results show that for ferrous metals and alloys the correlation between endurance limit and elastic limit is not good, but between endurance limit and tensile strength it is fairly good, and for reversed bending stresses averages 50 per cent of the tensile strength. Under truly axial stresses the endurance limit for reversed axial tension-compression is 75 to 110 per cent of that for reversed bending. For ordinary cases a safer ratio is 65 per cent.

829. Torsion Endurance Limit.—Tests show * that the endurance limit of steels for completely reversed torsion approximates 55 per cent of the endurance limit for completely reversed flexure, varying between 44 and 71 per cent. For non-ferrous metals the average value is about the same.

For torsion stresses not completely reversed, tests show that the range of stress is nearly constant for any ratio of minimum to maximum stress, and that the maximum stress cannot exceed a certain value which is in the neighborhood of the elastic limit. The diagram for torsion stresses would therefore be unlike the Goodman diagram.

830. Rapid Methods for Determining Endurance Limit.—J. H. Smith † found when a certain constant range of stress was applied to a specimen repeatedly, and the mean unit stress was gradually increased, that at a certain maximum unit stress the extensometer readings increased faster than the mean stress. The range determined in this way was found to agree with the endurance range as determined by the more tedious Wöhler method. This method has not been used by other investigators, but McAdam * has found an "endurance yield point" which he thinks is similar to that found by Smith.

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* See *The Fatigue of Metals*, Moore and Kommers, p. 147.

† *Jour. Iron and Steel Inst.*, 1910, Vol. 82, p. 246.

C. E. Stromeyer † has also suggested an accelerated test. He allowed water to flow around the specimen which was subjected to alternating torsion. By the use of thermometers which could be read to 0.01° C., he measured the temperature of the incoming and outgoing water. By his method the endurance limit is the maximum unit stress which will just generate heat in the test piece.

The method developed at the University of Illinois ‡ is similar in principle to that of Stromeyer, but is an improvement in that it uses a sensitive thermocouple for the detection of temperature change. While this method is reliable for many steels, tests have shown that it is not infallible, and cannot replace the long time test for reliable determinations of the endurance limit.

Gough § and Lea || independently developed an accelerated method based upon the fact that a rotating beam which has its load gradually increased will show a straight line relation between load and deflection up to the endurance limit, after which the deflection increases more rapidly than the load. This test also is not infallible for steel, and apparently is not applicable to non-ferrous metals.

Gillet and Mack ¶ shortened the time of fatigue tests by making use of the known fact that steels stressed at or just under the endurance limit are strengthened. They tested specimens to 1 or 2 million cycles, and then raised the stress. If the specimen failed at a shorter life than a virgin piece at that stress (which very seldom happened) it would appear that the original stress was slightly above the true endurance limit. If it lasted decidedly longer than a virgin piece (which usually happened) it afforded evidence that it would have lasted longer, and probably indefinitely, at the original stress. By this method the stress was raised after each 1 to 1½ million cycles until fracture occurred. The higher stress points were used merely as corroborative of a probable longer life at the lowest stress.

D. J. McAdam ** has made use of an "accelerated fatigue" method which is peculiar to an inertia torsion machine which he designed. In this machine when a specimen weakens under repetition of stress, the angle of

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* Amer. Soc. for Test. Mat., 1924.

† Proc. Royal Society, 1914. Vol. A-90, p. 411.

‡ Bulletin No. 124, University of Illinois, 1920, p. 159.

§ Engineering (London), 1921, Vol. 132, p. 159.

|| Engineering (London), 1923, Vol. 115, pp. 217, 252.

¶ Proc. Amer. Soc. for Test. Mat., 1924.

** Proc. Amer. Soc. for Test. Mat., 1924.

twist of the specimen, and hence the total amplitude of oscillation of the flywheel increases. The nominal stress, therefore, increases during the gradual yielding of the specimen and accelerates the fatigue. This method, then, consists in determining the stress above which the deflection, and hence the stress, increases automatically until the specimen breaks.

Moore and Wishart * have suggested a method based on the theory that cycles of repeated stress below the endurance limit increase the endurance limit and presumably the tensile strength, whereas for stresses above the endurance limit cracks begin to develop and reduce the tensile strength. The Rockwell hardness is determined on five or six fatigue specimens, which are then subjected to about 1,400,000 cycles in reversed bending, both above and below the estimated endurance limit. After this the tensile strength of the specimens is determined, the strength being called zero for specimens which failed. Making corrections proportional to the Rockwell hardness, the data are plotted using fatigue stress as ordinates and corresponding tensile strength as abscissas. The endurance limit is taken as the ordinate corresponding to the maximum abscissa.

At present, therefore, there is no accelerated test which can be confidently relied upon to determine the endurance limit. Any of the above methods may, however, be used to predict the probable value of the endurance limit, and in that way enable it to be determined by the use of only a few specimens. Since both the ultimate strength of steel and the Brinell hardness number show a fairly good correlation with endurance limit, these values may also be used to predict what the endurance limit is likely to be. Such predictions should always, however, be checked up by determinations made from actual long-time tests.

831. Bauschinger's Theory of Failure.—Bauschinger showed † that the elastic limits in tension and compression as ordinarily determined were variable limits, which in many cases had been artificially raised or lowered. When a bar was subjected to gradually increasing alternating stresses of equal amount in tension and compression, two equal elastic limits were set up in the bar. These he called the "natural" elastic limits, those determined in the usual way being called the "primitive" elastic limits. If the tensile elastic limit was raised by alternating stress, the compressive limit was lowered a definite, but not necessarily the same, amount. The elastic range found in this way under repeated stress was the same in magnitude as the maximum range which could be applied repeatedly to a bar without causing rupture. According to Bauschinger's theory, failure due to repeated stresses is caused by inelastic behavior, and, if stresses are kept within the "natural" elastic limits, failure will not occur.

The results obtained by Bauschinger were confirmed by Bairstow.‡ He found that iron and steel, after a sufficient number of cycles, were capable of adjusting themselves to variations of stress. When this adjustment was complete, the specimen was found to be perfectly elastic throughout the whole cycle, and fatigue did not occur. For some cases of completely reversed stresses observations were continued almost to the breaking point, but the extensometer gave no warning of the deterioration of the specimen. In other cases of stress from zero to a maximum, even though the stress was great enough to cause ultimate failure, the extensometer was not sensitive enough to detect the small changes which first occurred; but repetition of stress, however, made the changes measurable.

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* *Proc. A.S.T.M.*, Vol. 33, 1933, p. 334.

† See Unwin's *Testing of Materials of Construction*, p. 361.

‡ *Phil. Trans. Royal Society*, Vol. A210, 1910, p. 35.

832. Mechanism of Fatigue Failure.—As pointed out in Chapter XX, metals are composed of crystals, and the structure is by no means homogeneous. When a bar is deformed there will evidently be unequal distributions of stress among the crystals, and, when the stress becomes sufficiently great in the most highly strained crystals, they will give way by microscopic movement along their cleavage planes. This gliding is manifested by "slip lines" on the surfaces.

It has been shown by Ewing and Humphrey * that failure may occur in fatigue by an increase in the number of slip lines, a broadening of these lines, and the initiation of a crack along the broadened slip lines. However, it has also been shown by later experiments that slip lines may be produced without causing final failure.

Within the past few years two new methods of attack have been developed in attempts to determine basic changes in material preceding fatigue failure.

Gough † and his colleagues in England used precise X-ray diffraction methods to study the changes which the microscope cannot reveal. They found on a normalized mild steel that, whatever the type of stressing, and whether static or cyclic, the effect on the crystalline structure is one of destruction of the crystals. This leads to the material being always in one or more of three conditions: (*a*) perfect grain; (*b*) dislocated grain; and (*c*) crystallites, which are very small crystal fragments having random orientation.

Under fatigue stressing, at the first application of the maximum stress, some damage is caused by break-up, varying in amount according to the extent by which the stress exceeds the yield point. The endurance limit corresponds to the maximum range which will cause no further break-up. If the applied range of stress exceeds the safe range, break-up into crystallites sets in, causing destroyed structure in the immediate neighborhood of the crack.

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* *Phil. Trans. Royal Society*, Vol. 200, 1903, p. 241.

† *The Engineer*, April 30, 1937, p. 520.

Kommers,* in a different way, has investigated the effect of overstressing on the fatigue strength. Various specimens were subjected to, say, 10 per cent of overstress, for various numbers of cycles less than the number that would cause failure. By having a series of specimens, it was possible to determine the new endurance limits after specimens had been overstressed for various periods on the journey toward failure.

In each case the percentage by which the new endurance limit was below the virgin endurance limit was called the percentage of damage. It was thus possible to draw damage curves which showed the changes in fatigue properties as the specimen approached failure. These damage curves showed that for small numbers of cycles and small percentages of overstress it was possible to produce an actual increase in the original endurance limit. However, when the number of cycles increased, the percentage of damage usually increased also.

It has been shown by many experimenters that when a specimen is subjected to long periods of fatigue just below the endurance limit, the fatigue strength may be increased. This strengthening process seems to be a process of repetitive cold work. The tests on overstressing and understressing indicate that the endurance limit is not a fixed quantity, but one that may be manipulated by various stressing methods.

833. Formulae for Dimensioning Members Subjected to Fatigue.—Working independently of Goodman, J. B. Johnson † developed a diagram similar to that of Goodman. Johnson also developed a formula which was simplified by Barr, and which can be used in place of the diagram. The formula is:

$$S_{\max}=\frac{0.5\,S_u}{1-0.5\,r} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

in which $S_{\max}$ is the maximum unit stress during a cycle, S_u is the ultimate tensile strength of the metal, and r is the ratio of the minimum to the maximum unit stress of a cycle. The above formula is for unit stresses which would cause failure, and it should be noted that r will be negative if the stress is reversed.

A formula for working unit stresses may be employed by dividing S_u by a suitable factor of safety. The formula then becomes:

$$S'_{\max}=\frac{0.5\,S_w}{1-0.5\,r} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

in which S_w is a working unit stress.

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* *Proc. A.S.T.M.*, Vol. 38, 1938, p. 249.

† Johnson, *Materials of Construction*, 5th ed., p. 781.

Formula (2) will be illustrated by two examples.

Example 1.—Suppose that the minimum unit stress of the cycle is 0.7 of the maximum stress, and of the same sign. If the ultimate strength of the material is 60,000 lb. per sq. in., and the factor of safety is 4, determine the maximum working unit stress.

$$S'_{\max}=\frac{0.5\times 60{,}000}{4(1-0.5\times .7)}=15{,}000 \text{ lb. per sq. in.}$$

Example 2.—For the same material, with the minimum stress 0.5 of the maximum stress in the opposite sense, determine the maximum working unit stress with a factor of safety of 4.

$$S'_{\max}=\frac{0.5\times 60{,}000}{4(1+0.5\times .5)}=6{,}000 \text{ lb. per sq. in.}$$

Modified Johnson Formula.—In 1922 Moore, Kommers, and Jasper * suggested a modification of the Johnson formula, which was not based upon 0.33 as the ratio of the endurance limit for completely reversed stress to the ultimate tensile strength as required by the Goodman diagram. If S_1 is the endurance limit for completely reversed stresses, and S_0 is the endurance limit for stresses from zero to a maximum, the new formula is based upon an experimentally determined S_1 for each metal, but retains the ratio $1.5=\frac{S_0}{S_1}$, as required by the Goodman diagram. The formula is:

$$S_{\max}=\frac{3\ S_1}{2-r} \qquad (3)$$

in which the notation is the same as before.

A Modified Diagram.—There are a number of objections to the Goodman diagram, shown in Fig. 3, and the formulae derived from it. Comparatively few experiments have been made to verify the correctness of the diagram, and for ferrous metals and alloys the average ratio of endurance limit to tensile strength is more nearly 50 per cent rather than 33 per cent. A still more important objection is the fact that it would probably never be desirable to use a maximum stress in a cycle which exceeds the yield point of the material, because such a stress could cause undesirable permanent deformation.

Experiments made in Europe have suggested a modified diagram,† as shown in Fig. 6. The point C in the figure represents the value of the yield point, and OA and OB the endurance limit for completely reversed stresses. The abscissas represent the average or mean unit stress in the cycle, instead of an arbitrary scale as in the Goodman diagram. When the same scale is used for ordinates and abscissas, the line OC will be a 45-deg. line. Two straight lines are drawn from the yield point to the plus and minus values of the endurance limit for completely reversed stresses, and these lines represent the values of maximum and minimum stress.

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* *Proc. A.S.T.M.*, Vol. 22, 1922, p. 266.

† See "Design-Stress Diagrams," J. B. Kommers, *Product Engineering*, October, 1938, p. 395.

The formula which expresses the relationships in such a diagram is as follows:

$$S_{\max} = \frac{2\,S_1}{(1-r)+\dfrac{S_1}{S_y}(1+r)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

in which the notation is the same as before, and S_y is the yield point or yield strength.

The following relationships may be of interest in connection with Fig. 6. $\pm S_a$ = alternating unit stress in a cycle, S_{av} = mean or average unit stress in a cycle,

$$S_{\max} = S_{av} + S_a, \qquad S_{\min} = S_{av} - S_a, \qquad \text{and } S_{av} = \frac{S_{\max} + S_{\min}}{2}.$$

When the endurance limit for completely reversed stresses and the yield point or yield strength are known, a diagram like Fig. 6 may be easily constructed, and formula (4) may be used.

It should be understood clearly that the use of this diagram and formula is advocated only when the designer is working with materials for which complete information regarding the various fatigue limits for different ratios of r is not available.

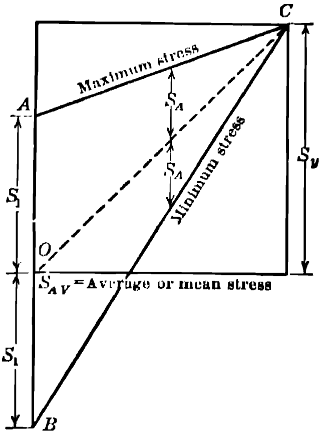

FIG. 6.—Modified Fatigue Stress Diagram.

Example.—A material has an ultimate tensile strength of 78,000 lb. per sq. in., a yield point of 52,200, and an endurance limit for completely reversed stresses of 34,000. If the minimum unit stress is 10,000 lb. per sq. in. compressive, and the maximum unit stress is 20,000 lb. per sq. in. tensile, determine the factor of safety for repeated stresses, and the factor of safety as based upon ultimate strength. In this case $r = -0.5$, and from formula (4): $S_{\max} = \dfrac{2 \times 34000}{(1+0.5)+\dfrac{34000}{52200}(1-0.5)}$ = 37,200 lb. per sq. in. The factor of safety for repeated stresses is, therefore, 37,200 divided by 20,000, or 1.86. The factor of safety with respect to the ultimate strength may be found by considering that the point C in Fig. 6 corresponds to the case of static loading, when r is unity, and the alternating stress is zero. In this case the ultimate strength is $1.5\,S_y$; therefore 1.5 multiplied by 1.86, or 2.79, is the factor of safety with respect to the ultimate.

834. Corrosion Fatigue.—In 1917 B. P. Haigh * showed that the simultaneous action of repeated stress and a corroding agent may reduce the ordinary fatigue strength of a metal. D. J. McAdam, in the United States, has studied this subject very exhaustively, and a large amount of work has been done on corrosion fatigue both here and abroad.

With fresh water as the corroding agent, the endurance limit or corrosion-fatigue limit for carbon steels and ordinary alloy steels ranges from 66 to less than 15 per cent of the endurance limit in air. The corrosion-fatigue limit is still lower when salt water is the corroding agent. The corrosion-fatigue limit seems to be improved very little either by heat treatment or by chemical composition, unless such heat treatment or composition affects corrosion resistance. For "stainless" (high-chromium) and other corrosion-resistant steels, the corrosion-fatigue limit is higher than for carbon steels and other alloy steels.

Figure 5 shows curves indicating the approximate reduction of endurance limit which may be expected with fresh and salt water corrosion.

In 1937 Gough † reported on six different materials, both ferrous and non-ferrous, and stated that, using a salt spray for the corroding medium, no endurance limit was found. These results would indicate that any unit stress, however small, will finally cause failure if continued long enough.

835. Fatigue Tests of Riveted Joints.—There is at present a definite interest on the part of engineers in determining the fatigue properties of structural and machine members, rather than merely determining the fatigue properties of specimens cut from these members. The presence of rivet holes, mill scale, abrupt changes of cross-section, and other stress concentration effects tend to reduce the endurance limit of such members below the value obtained for polished fatigue specimens.

The fatigue tests on riveted joints reported by Wilson and Thomas ‡ show some interesting comparisons. Table 4 gives the fatigue strength of polished specimens, plates in two different conditions, and plates of the actual riveted joints. The test specimens in each case were subjected to stresses from zero to a maximum tension.

These results indicate that the plates of the riveted joints have about the same fatigue strength as the plates affected by the stress concentration of drilled holes and mill scale. The results also show that as the static strength of the plates increases the effect of stress concentration increases. This is a confirmation of some of the curves shown in Fig. 5.

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* *Jour. Inst. of Metals* (Brit.), Sept. 19, 1917, p. 55.

† *Engineering*, Vol. 143, 1937, p. 673.

‡ *Bulletin* No. 79, University of Illinois, 1938.

TABLE 4.—FATIGUE STRENGTH OF VARIOUS TYPES OF STRUCTURAL STEEL SPECIMENS

Type of Specimen	Strength, lb. per sq. in.		Ratio of Fatigue Strength to Static Strength	Ratio of Fatigue Strength to Fatigue Strength of Polished Specimen
	Static	Fatigue		
CARBON STEEL				
Round, machined and polished	64,700	47,000	0.73	1.00
Plate, with mill scale on two sides	61,800	30,300	0.49	0.67
Plate, with mill scale on two sides and 1⅛-in. drilled hole	61,800	21,200	0.34	0.47
Plates of riveted joints	63,600	25,900	0.41	0.56
SILICON STEEL				
Round, machined and polished	81,700	56,000	0.69	1.00
Plate, with mill scale on two sides	81,800	35,800	0.44	0.64
Plate, with mill scale on two sides and 1⅛-in. drilled hole	80,800	23,900	0.30	0.43
Plates of riveted joints	80,200	25,600	0.30	0.43
NICKEL STEEL				
Round, machined and polished	99,000	74,000	0.75	1.00
Plate, with mill scale on two sides	99,000	39,500	0.40	0.53
Plate, with mill scale on two sides and 1⅛-in. drilled hole	99,000	24,300	0.25	0.33
Plates of riveted joints	99,000	26,700	0.27	0.36

836. Fatigue of Non-ferrous Metals.—The results discussed thus far in this chapter have to do mostly with wrought ferrous metals. Very little information is available on the fatigue strength of cast steel or cast iron. The study of non-ferrous metals and alloys is being carried on at the present time, and results thus far indicate that in many respects there is considerable similarity in the behavior of ferrous and non-ferrous metals in fatigue. Both types of metal show a higher endurance limit for cold-worked metal than for annealed metal. Both show increased fatigue strength from stressing below the endurance limit. Both show poor correlation between endurance limit and proportional limit or percentage of elongation. Both show marked reduction in endurance limit due to the presence of notches or sudden changes in cross-section. In both metals the effect of notches is not as serious as the calculated local increase of stress would indicate.

R. R. Moore * found for some light-weight aluminium-magnesium alloys that the endurance limit was determined at 1,000,000 cycles. On the other hand, at the University of Illinois tests on monel metal have been carried out to 500,000,000 cycles without any indication of an endurance limit. These and other results indicate that there is great variability in non-ferrous metals in the number of cycles to which tests must be carried to determine the endurance limit. Fig. 7 shows some characteristic S-N diagrams for non-ferrous metals, obtained at the University of Illinois.*

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* *Proc. Amer. Soc. Test. Mat.*, 1924.

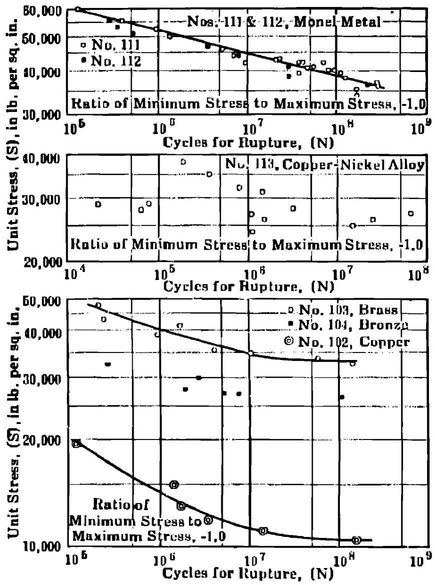

Fig. 7.—S-N Diagrams for Reversed Flexure Tests, Monel Metal, Copper-Nickel Alloy, Annealed Brass, Annealed Bronze, and Annealed Copper. Brass, No. 103, 60% Cu. 40% Zn. Bronze, No. 104, 95% Cu, 5% Sn.
(From *Bulletin* No. 142, University of Illinois.)

R. R. Moore found for the light-weight alloys mentioned above that the ratio of endurance limit to ultimate tensile strength varied from about 0.26 to 0.39. This is less than is usually the case with ferrous alloys. He also found that it seems to be more common with non-ferrous alloys than with steel to have the endurance limit greater than the proportional elastic limit in tension. This fact taken in conjunction with the previous statement indicates that the proportional elastic limit of these alloys was a smaller proportion of the ultimate tensile strength than is usually the case with ferrous alloys.

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* *Bulletin* No. 142, University of Illinois, 1924, p. 63.

CHAPTER XXIX

THE CORROSION OF METALS*

By O. P. Watts†

837. Importance to the Engineer of a Study of Corrosion.—For nearly a century the problem of preventing the corrosion of metals has engaged the attention of scientific and practical men, and an enormous amount of experimental work has been done on this subject; yet we are still far from a satisfactory solution of the problem. With the enormous present use of metals this subject has become more important than ever before to every manufacturer and user of metals, to all owners of structures in which metal is largely employed, and to every engineer who has to deal with the construction or use of modern buildings or machinery. Even reinforcement deeply buried in concrete is not immune from corrosion. The statement of an eminent chemical engineer, that "rust taxes the people of the United States $7,000,000 annually," is probably an under- rather than an over-estimate. Over 60 per cent of the zinc produced in and imported into this country is used for galvanizing,‡ to fight rust. Each year sees a larger extent of metal surfaces exposed to corrosive influences, and therefore the tax levied on human industry by the corrosion of metals is continually increasing. When to the direct loss due to the destruction of metal there is added the cost of paints and other coatings used to prevent corrosion, the total tax chargeable to this source is stupendous.

Since the rusting of iron is the most important case of corrosion, and because it has been through the study of this phenomenon that our present conceptions of the nature of the process of corrosion of metals has been chiefly derived, it is fitting that this should receive special attention.

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* References: Sang's *Corrosion of Iron and Steel.* McGraw-Hill, 1910.

Cushman & Gardner's *Corrosion and Protection of Iron and Steel.* McGraw-Hill, 1910.

Friend's *Corrosion of Iron and Steel.* Longmans. 1911.

Metal Corrosion and Protection. A very complete bibliography. Published by Carnegie Library of Pittsburgh. 1909. 64 p. 10 cents.

† Associate Professor Emeritus of Chemical Engineering, The Univ. of Wisconsin.

‡ W. A. Cook in *Metal Worker*, 1916, 85, 849.

838. Great Variation in the Durability of Iron.*—Cast-iron water pipe laid in France between 1664 and 1668 was in use in 1904, and probably still supplies water to the great fountains of Versailles. London and Glasgow have records of 120 years of service from cast-iron water pipe.

One of the most remarkable examples of the durability of iron is the column of Kuntab Minar erected at Delhi, India, 900 B.C., which is still in excellent condition after nearly 3000 years exposure to the weather. An American example of remarkable longevity in wrought iron was the suspension chains of the old bridge over the Merrimac River at Newburyport, Mass., which was removed in 1909 after 99 years of service. The chains were seemingly good for another century of use, in spite of the fact that they had been exposed to the weather without any protection for the greater part of this period.

On the other hand "in 1869 the British troop ship *Megaera* had to be beached at St. Paul's Island to prevent her sinking. Among other serious defects was a copper strainer fitted to a bilge suction pipe in a remote part of the ship. The action set up by it was sufficient to eat a hole right through the plates, and so admit water to such an extent that the ship had to be run ashore to save the crew." †

Cases of the corrosion of boilers and of the copper and brass tubes of the condensers of marine engines have been described frequently, but at too great length to be quoted here.

839. Validity of the Acid Test for Determining the Relative Resistance of Metals to Corrosion.—Until comparatively recently most experimental work on the resistance to rusting of various kinds of iron and steel was based on corrosion by acids; but it is now generally admitted that the acid test is not capable of determining the relative durability of different varieties of iron and steel under atmospheric conditions, and although this test will doubtless still be frequently employed, its findings will not be considered conclusive. The only reliable test appears to be that of subjecting the materials to actual working conditions, a process which usually defers the verdict for a number of years.

840. Relative Resistance to Corrosion of Wrought Iron, Cast Iron, and Steel.—In the last 75 years numerous tests have been carried out for the purpose of ascertaining the relative resistance to corrosion under various conditions, of wrought iron, cast iron, and steel. The most extensive of the early investigations are those of Mallet ‡ on the action of air and water on a hundred different makes of these three materials. Summaries of many later experiments may be found in Chapter 15 of Friend's *Corrosion of Iron and Steel*. From more recent experiments there appears to be little choice between good, modern wrought iron and steel as regards resistance to corrosion when exposed to the atmosphere, to sea water, or used as boiler tubes, or as pipes in water systems. Stahl * finds that "steel and iron tanks for storing sulphuric acid last equally well."

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* *Mech. Eng.*, 34, 372; *Am. Soc. Civ. Eng.*, 1867 (1), 26; *Inst. Civ. Eng.*, 1853, 12, 487.

† Admiral Corner in *Jour. Inst. of Metals*, 1911, 5, 115.

‡ *Report of Brit. Assoc.*, 1839, 1840, 1843.

The remarkable durability of cast-iron water mains has been shown by the examples already cited. In cases of corrosion by current straying from street railway tracks a similar leaching out of the iron often occurs, so that it is possible to drive a nail deeply into, or even entirely through a pipe that appears sound. Besides showing a lesser rate of corrosion both inside and outside, cast iron has an advantage over steel for water pipes in an initial thickness six or seven times as great. Another factor in the greater durability of cast-iron pipe appears to be the scale formed on the outside of the casting by contact with the sand of the mold. The removal of this increased two to four fold the rate of corrosion by air and by sea water.†

841. Pitting.‡—In the use of metal for roofing, pipes, tanks, etc., the way in which the corrosion is distributed over the surface may be quite as important a factor in determining its usefulness as the actual weight of metal removed or converted into rust. If corrosion takes the form known as pitting, it is evident that the removal of a very small amount of metal may end its usefulness; whereas, if the corrosion takes place uniformly over the whole surface, very many times this amount of metal may be removed before the apparatus fails to serve the purpose for which it was intended. In neutral or faintly alkaline solutions in which the rust initially formed remains attached to the metal, the rusting of wrought iron and steel almost invariably takes the form of pitting, i.e., deep corrosion confined to small spots here and there on the surface. An explanation of this peculiar type of corrosion is given under the effect of rust, Art. 849.

842. Dissolved Air Stimulates Corrosion.—It is generally recognized that the presence of air in solutions stimulates the rusting of iron and the corrosion of many other metals and alloys. In 1843 Mallet § said, "It would be desirable that the feed-water of marine boilers were heated to above 190° F. before entering them, and means provided for the escape of the air disengaged, which now enters the boilers and aids much in corrosion." Since that time the same recommendation has been reiterated again and again.‖ Not only is the corrosion of iron by hot water greatly lessened by removal of the air, but pipes carrying aerated cold water are often similarly benefited.

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* Sang's *Corrosion of Iron and Steel*, p. 59.

† Thwaite, *Jour. Iron and Steel Inst.*, 1880, (2), 667.

‡ Matheson, *Jour. Iron and Steel Inst.*, 1909 (1), 105; Rosenhain, *Trans. Faraday Soc.*, 1916, 237.

§ *Rep. Brit. Assoc. for Adv. Sci.*, 1843, 12.

‖ Walker, *Trans. Amer. Electrochem. Soc.*, 1908, 14, 186; Speller, *Mech. Eng.*, 1916, 37, 245.

843. Local Couples.—Whenever two electrical conductors of unlike materials are in contact with each other in an electrolyte a voltaic cell is formed, and there is a flow of current in the solution between them, one being anode and dissolving, if it is soluble in that particular solution, and the other being the cathode by which the current leaves the electrolyte. The effect of such short-circuited voltaic cells, or " local couples," in accelerating the corrosion of ordinary metals and alloys has been recognized and studied for nearly a century.

An example of this is found in a report on the Panama Canal under date of January, 1915.* " The top gate-valve seal is of cast steel and is held in place by bronze bolts. In practically every instance corrosion has been excessive around the heads of the bronze bolts, cutting away the metal and in some cases allowing the bolts to loosen and fall out."

844. Purity a Factor in Corrosion.—It is evident from a consideration of the corrosive effect on iron of contact with many other metals and alloys, that electro-negative materials present as impurities in iron and steel, or intentionally added as in making alloy steels, are likely to have an accelerative effect on corrosion. From this standpoint wrought iron of the highest grade would be expected to resist corrosion better than steel, and the superior endurance of ancient iron over modern steel has often been attributed to the greater purity of the former. Several manufacturers have adopted " purity " as their slogan, and have put on the market iron of exceptional freedom from impurities, claiming that their products resist rusting better than any other sheet iron or steel.

In direct opposition to the advocates of highest purity are those who add 0.1 to 0.25 per cent of the electro-negative metal, copper, to iron, claiming that experiment † shows such " impure iron " to resist atmospheric corrosion and attack by acids better than the pure irons. It is even contended that the remarkable durability of the iron of our forefathers, whose praises have been sung by many recent writers, owes its durability to the presence of a small amount of copper.‡

845. Effect of Mill-scale on Rate of Rusting.—One of the most commonly occurring negative materials which comes in contact with iron is the scale of black oxide which forms whenever iron is heated in contact with the air. This was early recognized as an accelerator of the rusting of iron, and its complete removal is specified, not only before painting or coating iron with some other metal, but whenever it is to be exposed to corrosive conditions. Although mill-scale itself is very resistant to corrosion, it is brittle and therefore liable to be broken off in spots, and always contains cracks, so that when wet a short-circuited voltaic cell is formed, in which iron as anode corrodes more rapidly per unit of area exposed to the electrolyte than if the scale were not in contact with it.

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* *Eng. News*, 1916, p. 1005.

† D. M. Buck, *Jour. Ind. and Eng. Chem.*, 1913, 5, 447; 1916, 8, 209.

‡ O. W. Storey, *Trans. Amer. Electrochem. Soc.*, 1917, 32, 211.

Oxide dissolved in steel should also accelerate rusting. Speaking of specimens of steel polished for metallographic examination, some of which contain oxide and others do not, Law says:* "If these are kept side by side in an ordinary room, it will be seen that the steels containing oxide begin to show signs of rusting long before the others, and in dilute acid solutions they corrode far more readily."

846. Nature of the Process of Rusting.—In spite of its occurrence for ages, it is only recently that the process of the formation of rust has been understood. It has long been known that oxygen and moisture are necessary for the rusting of iron, but the exact part played by each was not known. The two modern theories of the rusting of iron are the *Acid* and the *Electrolytic Theory*. According to the former the presence of an acid is necessary to the formation of rust, but even so weak an acid as carbonic may serve. The acid causes the metal to dissolve, and the oxygen changes the dissolved metal to rust, thereby liberating the acid, which is then capable of dissolving more metal, and so the process goes on. After several years of careful experimenting by different investigators, it now seems to be established that moisture and oxygen are sufficient for the continued rusting of iron, so that the electrolytic theory of rusting is the one more generally accepted.

The electrolytic theory postulates that when a metal dissolves it goes into solution as ions, i.e., atoms each carrying one or more (according to its valence) electric charges, and that it is only by giving up its charge that a metallic ion can escape from solution and become metal again. In the electrolytic cell this is merely visualizing Faraday's law, that the passage of a given quantity of current through an electrolyte is accompanied by the dissolving of a definite amount of material from the anode, and the deposition of a chemically equivalent amount at the cathode. All that the electrolytic theory of the solution of metals has done is to extend the operation of Faraday's law, previously confined, in men's minds, to electrolytic and voltaic cells, to every case of the dissolving of metals. Although no flow of current can be detected when a piece of iron is dissolving in acid, it is believed that the ions of metal still carry electric charges into the solution and that the hydrogen displaced from the acid also carries its normal electric charge, just as if the metal were caused to dissolve as anode and the hydrogen to be deposited at some cathode by the application of an electromotive force external to the cell.

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* *Jour. Iron and Steel Inst.*, 1907 (2), 103.

847. The Function of Hydrogen in Corrosion.—The statement is sometimes made that it is the hydrogen of acids that corrodes metals. It is evident that this is not so. The function of the hydrogen of acids in corrosion is merely to supply ions that are easily displaced from solution by metals, and which also escape from their surfaces and so do not prevent free access of the electrolyte, as is the case with many metallic ions, which, though more easily displaced than hydrogen, adhere more or less firmly to the surface of the metal on which they are deposited.

848. The Function of Oxygen in Corrosion.—So far there seems no need for oxygen in the electrolytic theory of the rusting of iron; but the dissolving of iron or any metal in an acid or any other electrolyte is (except where a change from a higher to a lower valence can occur, as with ferric salts) a case of displacement. Solution and deposition are inseparable; if deposition is prevented, the process of solution is also halted. It is here that oxygen comes into play as a deciding factor in corrosion. If two sheets of copper connected by a wire are suspended in a solution of copper sulphate, copper neither dissolves nor is deposited; the tendency toward solution or deposition at one plate is balanced by an equal tendency at the other. That solution shall occur it is necessary that a slight E.M.F. be applied to the system, when not only does copper dissolve from one sheet, but an equal weight of metal is deposited at the other.

In order that a metal shall dissolve in an electrolyte, e.g. hydrochloric acid, it is necessary that the forces tending toward solution and deposition shall be unequal. This idea has been stated in various ways: that the chemical affinity of the metal for the acid radical must exceed that of hydrogen for the same; that the potential of the metal must be greater than that of hydrogen; that the potential of the metal must be greater than the discharge potential of hydrogen on it; or that the solution pressure of the metal must exceed that of hydrogen. Not only does it require a greater driving force to displace hydrogen on one metal than on another, but the force or potential required increases with the amount of hydrogen already displaced and present on the surface of the metal. It follows then, that the dissolving of a metal may begin in some electrolyte from which it displaces hydrogen, but may be brought to a standstill before gas becomes visible and escapes, because the potential of the metal, or driving force, is no longer great enough to continue displacing hydrogen on a metal already highly charged with it. The only way in which dissolving of the metal can then continue is for a portion of the hydrogen to be removed by some means, so that the force required to deposit more of it may again be less than the potential of the metal. To do this is the function of oxygen in the rusting of iron, first clearly stated by W. H. Walker in 1907.* "It was formerly thought that the action of oxygen as a factor necessary in corrosion was simply to oxidize the iron ions thrown into solution, and to precipitate them as rust. While it is true that this reaction does take place, and is indeed the most striking function that oxygen performs, it is really a secondary one, which is simply incidental to corrosion and not a necessary part of the action. Its real accelerative effect is due to the fact that it depolarizes the hydrogen which is set free by the reaction, and separates out on the metallic iron.* Confirmation of this view of the function of oxygen in corrosion is seen in experiments on the corrosion of metals in acids,† in which the addition of oxidizing agents caused the rapid dissolving of several metals by acids which alone have little or no action on them.

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* *Jour. Amer. Chem. Soc.*, 29, 1264.

849. Conditions Affecting Corrosion.—The corrosion of metals, including the rusting of iron and any other process which involves as a preliminary step the dissolving of a metal, requires an electrolyte. The rate of corrosion is determined by Ohm's law, i.e., it varies directly as the E.M.F. and inversely as the resistance. Other conditions being equal the lower the resistance of the electrolyte the more rapidly is the metal attacked. The rapid increase in the rate of corrosion observed with rise of temperature is due in part at least to the lessened resistance of electrolytes at high temperatures.

It is of course to be expected that a metal will not dissolve in an acid which forms an insoluble salt with it; why acids attack some metals readily, but not others, although the salts of both are soluble, may be understood by a study of the following table:

TABLE 1

Element.	Potentials * in Normal		Discharge Potential of Hydrogen on Metal.		Difference.	
	Sulphate.	Chloride.				
Zn	0.524	0.503	Hg	0.548	Fe	....
Cd	0.162	0.174	Zn	0.468	Zn	0.056
Fe	0.093	0.087	Pb	0.408	Ni	.000
Sn	....	−0.085	Sn	0.298	Cd	−0.083
Pb	....	−0.095	Cd	0.248	Sn	−0.383
H	−0.238	−0.249	As	0.152	Pb	−0.503
Cu	−0.515	....	Cu	−0.002	Cu	−0.516
As	....	−0.550	Ni	−0.022	As	−0.708
Hg	−0.980	....	Ag	−0.082	Ag	−0.882
Ag	−0.974	....	Pt	−0.112	Pt	−1.028
Pt	....	−1.140	Au	−0.218	Au	−1.144
Au	....	−1.356	PtPt	−0.238	Hg	−1.528

* Neuman, *Zeit. für Phys. Chem.*, 1894; 14, 203.

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* W. H. Walker, *Jour. Iron and Steel Inst.*, 1909 (1), 69.

† *Trans. Amer. Electrochem. Soc.*, 1917, 32, 17.

Corrosion of a metal by acids and by solutions of the salts of other metals can be predicted from Table 1. Except as limited by the insolubility of its salt, a metal is corroded by solutions of all metals below it in potential. If the potential of a metal exceeds the discharge potential of hydrogen on it, this metal is readily corroded by acids whose salts of the metal are soluble; but if its potential is less than the discharge potential of hydrogen, acids dissolve it only at the rate at which the displaced hydrogen dissolves in the electrolyte, is removed by the oxidizing action of the air, or is otherwise disposed of. The special power possessed by nitric acid of dissolving lead, copper, silver, etc., whose potentials are less than the discharge potential of hydrogen on them, is due to its being an oxidizing agent as well as an acid.

The order and relative magnitude of the potentials of the metals not only foretells what metals will displace others from solution, but gives the order of chemical activity, and the stability of compounds of the different metals, those of higher potential being more active and forming more stable compounds. The discharge potential of hydrogen is the potential produced by the accumulation of hydrogen on the metal to such a degree that it begins to escape in visible bubbles. The column marked " difference " is the result of subtracting the discharge potential of hydrogen from the potential of the metal, and its magnitude should be an index of the rate of corrosion of the different metals by acids, provided no oxygen or oxidizing agent is allowed access to the metal. For example cadmium is very high in potential, and from this consideration alone might be expected to be corroded rapidly by acids, but the negative value of the " difference " indicates that it should dissolve in non-oxidizing acids only at the rate at which the displaced hydrogen is removed by the electrolyte; this accounts for its slow corrosion when used as a reference electrode in the 30 per cent sulphuric acid of a lead storage battery.

The protection of iron from rusting by immersion in a 5 per cent solution of sodium hydrate is predicted by the value −0.90 for the " difference "; iron is incapable of displacing hydrogen from this solution, hence does not dissolve, and no rust can form. The effect upon the corrosion of iron of electro-negative impurities such as particles of graphite, bits of scale left on the surface, or the cementite present in steels, is not simply a matter of the initial E.M.F. between the iron and the other substance, but depends on the diffrence between the potential of iron and the discharge potential of hydrogen on these materials.

There are doubtless many incorrect values in the table, as most of the data is old, so that conclusions drawn from it can be relied on only in a broad and general sense.

The effect of amalgamation in preventing the dissolving of zinc by acids is due to the fact that the discharge potential of hydrogen on mercury exceeds the potential of zinc; the remarkable diminution in the rate of attack of iron by sulphuric or hydrochloric acid, caused by the addition of a solution of arsenic, is due to a similar action—arsenic is precipitated on the surface of the iron and serves as cathode in the voltaic cell of which iron is anode; but the discharge potential of hydrogen on arsenic exceeds the potential of iron, hence iron is unable to displace hydrogen from the electrolyte except as an infinitesimal layer, and corrosion ceases.

850. Rust a Stimulator of Corrosion.—In 1849, R. Mallet [*] said, "As every metal is positive to its own oxides, the adherent coat of rust upon iron, while it remains, powerfully promotes the corrosion of the metal beneath." Experiments on atmospheric corrosion of wrought iron, open hearth and Bessemer steels by Aston and Burgess [†] showed rust to have an accelerating effect in every case. In a later paper Aston [‡] ascribes the accelerating effect of rust on the corrosion of iron to its acting as a screen to prevent free access of air to the metal beneath it. "The underlying feature appears to be the relative access of oxygen to the surface of the electrodes. The electrolyte must reach both; then that to which oxygen has the more free access becomes the cathode, and the other is the anode. If two bare iron electrodes are separated by a partition of porous earthenware, parchment, etc., either may be made the cathode by bubbling air into this compartment, and not into the other. . . . Wet rust or a similar coating upon one electrode plays the role of a diaphragm permeable to the moisture, but preventing or slowing down the oxygen penetration." This theory of the function of rust seems adequate to account for the observed tendency for the corrosion of iron and steel to take the form of pits when it corrodes under such conditions that the first-formed rust is not continually removed. Pitting does not occur in the corrosion of iron or steel by acids or as anode in the refining of iron electrolytically, but the corrosion of these materials almost invariably takes this form when they are buried in the ground or immersed in a stagnant, neutral electrolyte, so that the patches of rust first formed can adhere. Whether steel corrodes uniformly or in pits, is then determined, not by the nature of the steel, but by its surroundings. Given uniform surroundings corrosion will be uniform; with freer access of the depolarizing air to some spots than to others pitting results.

851. Concentration Cells and Thermal E.M.F. May Cause Corrosion.—It has long been known that an E.M.F. exists between two pieces of the same metal immersed in an electrolyte that differs in concentration at the electrodes; this constitutes a "concentration cell," and although the E.M.F. is small, its continued action in good-conducting electrolytes is often responsible for serious corrosion.

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[*] *Report of Brit. Assoc. for Adv. of Sci.*, 1849, p. 111.

[†] *Trans. Amer. Electrochem. Soc.*, 1912, 22, 233.

[‡] *Trans. Amer. Electrochem. Soc.*, 1916, 29, 449.

Burgess and Engle [*] have shown that an E.M.F. is produced between two pieces of iron in an electrolyte when one of them is heated to a higher temperature than the other, and have suggested that this may explain many cases of corrosion of the tubes of locomotive boilers. Several years ago a severe case of corrosion occurred in the steel water-jacket of a copper blast-furnace at Douglas, Ariz.,[†] the inner plates of which were deeply corroded, while the outer plates and stiffeners were unattacked. The absence of acidity in the water, and the entire freedom from corrosion of boilers using the same water were puzzling features of the case. The corrosion can be fully accounted for by the existence of an E.M.F. between the highly heated inner shell as anode and the cooler outer part as cathode, the water, which was found to contain much sodium and potassium as sulphate, chloride, and carbonate, furnishing the electrolyte. On account of its alkalinity the water could not attack iron except the metal was anode, and hence did not corrode the boilers, where the E.M.F. was lacking, or at least was very much smaller due to more uniform heating.

852. Effect of Stress and Strain on Corrosion.—Several investigators have studied the effects of stress and strain on the potential and corrodibility of iron and steel,[‡] as a result of which it may be concluded that the cold-working of steel or iron raises its potential and increases the rate at which it is corroded by acids. Fig. 1 shows results obtained by Thickens in corroding, in N/4 hydrochloric acid, cylinders of iron and steel that had been strained by torsion or in tension, A and B being mild steel, C, electrolytic iron, and D a cylinder of mild steel that was stretched until necking down occurred, when it was machined to a true cylinder and suspended in the acid. Fig. 2 shows the effect of corrosion by acid on a punched plate of half-inch steel; not only was there severe corrosion of the strained metal at the hole, but curious lines of strain are seen to extend to a distance of an inch from the hole.

With regard to stresses which do not produce permanent distortion of the metal, i.e., which are within the elastic limit, the results of different experimenters are so conflicting that this question must be regarded as still undecided.

853. Puzzling Corrosion of Turbine-driven Propellers.[§]—With the general adoption of bronze instead of cast iron or steel for the propellers of steamships it seemed as if the former troubles from corrosion were forever ended, and that the propeller might be regarded as a permanent piece of equipment. In 1908, however, *The Engineer* announced a new variety of corrosion which, in a few weeks or even days, destroyed the best bronze propellers. In consisted of pitting to the depth of three-quarters of an inch or more over an area of 40 to 50 square inches on the driving or astern face of the wheel.

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[*] *Trans. Amer. Electrochem. Soc.*, 1908, 13, 37.

[†] *Trans. Amer. Inst. Min. Eng.*, 1908, 38, 877.

[‡] Barus, *Bull. U. S. Geol. Survey*, No. 94, 48–73; Andrews, *Proc. Inst. Nav. Eng.*, 1894, 118, 356; Hambuechen, *Bull. Univ. Wis.*, No. 42; Richards and Behr, *Pub. Carnegie Inst.*, 1906; Walker and Dill, *Trans. Amer. Electrochem. Soc.*, 11, 153; Thickens *Thesis, Univ. Wis.*, 1908; *Trans. Amer. Electrochem Soc.*, 1908, 13, 7.

[§] *The Engineer*, 1908, 105, 535, 539; 1909, 107, 397; 1910, 110, 252. *Engineering*, 1912, 93, 33, 687, 884; 1913, 96, 690, 726, 761; 1914, 97, 535.

This peculiarly destructive form of corrosion was first noticed on the propellers of ocean-going destroyers of the British navy, and, curiously, was confined to vessels driven by turbine engines. Corrosion was so serious that a propeller was often ruined during the trials, and before the vessel was put into service. Later it was found that this form of corrosion was also taking place, but much more slowly, on the *Mauretania*, *Lusitania* and a few other "liners." In the interesting and lengthy discussion which followed the cause was assigned to faulty material, segregation of impurities, oxidation of the metal by air drawn from the water by "cavitation," erosion by the water due to the high speed of turbine engines, and to electrolytic action between strained and unstrained metal. A study of the examples shown in the several articles leads to the conclusion that the true cause is that last mentioned, and that corrosion may be prevented by (*a*) lessening the power transmitted by a single wheel, (*b*) the substitution of a stronger material for that used, (*c*) increasing the thickness of the wheel.

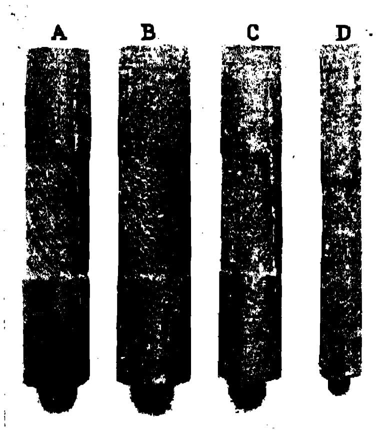

FIG. 1.

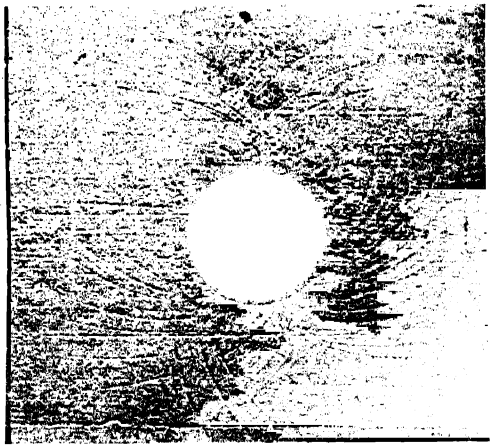

FIG. 2.

In many cases bending of the blades was found to have occurred at the places corroded. Corrosion was the result of a rise in potential of the metal caused by cold-working, and illustrates the serious damage that may be caused by an exceedingly small E.M.F., provided a good electrolyte is continually present. It is still an open question whether or not a portion of the observed corrosion is due to that bending of the blades within the elastic limit, which must occur while the vessel is running, but which does not result in permanent distortion of the propeller.

These examples of corrosion induced by strains indicate the desirability of annealing all metals and alloys which are likely to be subjected to corrosive influences.

864. Effect of Various Elements on the Corrodibility of Iron and Steel.—From the nature of the constitution of alloys it is evidently impossible from a mere knowledge of the resistance to corrosion of the alloying elements to predict correctly regarding corrosion of alloys, either by acids or on exposure to the atmosphere. Corrosion will be affected, not only by the chemical activity or resistance of the element added, but by the state in which this exists in the alloy. Whether the alloying element unites with the original metal forming a compound, forms a solid solution with it, or separates in the elemental state, are quite as important factors in determining corrosion as is the chemical nature of the alloying element itself. The quantity of the alloying element added will also influence profoundly the corrodibility of the alloy; if the added element forms with the original metal a compound which is strongly resistant to corrosion, and on which the discharge potential of hydrogen is less than on the original metal, its addition in small amounts will accelerate corrosion by forming active local couples; but as the amount added is continually increased a point is finally reached at which the alloy consists entirely of the compound, when the resistance of the alloy to corrosion will be far greater than that of the original metal.

When the constitution of alloys is thoroughly known and their corrosion has been more fully studied, it will probably be possible to predict correctly the corrodibility of many alloys before making them; but at present experiment is the only safe guide regarding the corrosion of most new alloys.

Heat treatment is an important factor in the corrodibility of alloys, for besides removing differences of potential due to strain, it often produces changes in the constituents of the alloy.

The effect on corrosion of adding other elements to iron has been extensively studied, but lack of space permits mention of the effects of only a few of the more common ingredients of steel.

Carbon.—Corrosion of annealed steel in water and dilute sulphuric acid rises with the carbon content to a maximum at the eutectoid point (.89 per cent C). Quenched and tempered steels show a continuous rise in corrosion with increase of carbon up to 0.96 per cent.* The temperature to which a quenched steel is reheated has a marked effect on its corrosion in 1 per cent sulphuric acid,† a steel containing 0.95 per cent carbon showing a sharp rise in solubility when reheated to 400° C., amounting to six times the rate of attack on untempered steel.

Copper.—The remarkable lessening of the corrosion of iron by the atmosphere, water, sea water, and acids, caused by the addition of very small amounts of copper, has been the subject of many investigations.‡ Although resistance to corrosion increases with the copper content up to 2 to 3 per cent of copper, for resisting atmospheric corrosion there appears to be no advantage in exceeding 0.25 per cent of copper, and quantities as small as 0.05 per cent are said to have a marked influence on the rate of corrosion of iron.

Manganese.—It is generally accepted that manganese in steel causes increased corrosion. Hadfield and Friend § found 0.7 per cent of manganese to cause a great increase in the rate of corrosion of carbon steels in tap water and in artificial sea water, but above 2 per cent of manganese corrosion is much decreased. In 0.1 and 0.5 per cent sulphuric acid corrosion increases with the manganese content up to 12 per cent manganese, the highest manganese used.

Oxygen.—From theoretical considerations combined oxygen would be expected to accelerate the corrosion of iron, and Law || corroborates this by observations on rusting and corrosion in dilute acid.

Silicon.—Silicon-iron alloys containing about 15 per cent of the former element are now extensively used under various trade names for the construction of chemical apparatus, although their hardness and brittleness are a serious drawback to their usefulness. Up to 20 per cent of silicon, iron silicide (Fe_2Si) forms a solid solution with iron, which fact, in connection with the small weight of silicon needed to produce a large quantity of the highly resistant iron silicide, accounts for the great resistance to acids secured by the addition of only a moderate amount of silicon, in comparison with additions of other elements for protection.

Sulphur.—"Sulphur is universally regarded as a stimulator of corrosion." ¶

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* Chapelle, *Jour. Iron and Steel Inst.*, 1912 (1), 270.

† Hadfield and Friend, *Jour. Iron and Steel Inst.*, 1916 (1), 48.

‡ F. H. Williams, *Proc. Eng. Soc. West Penn.*, 1900, 16, 23; Stead and Wigham, *Jour. Iron and Steel Inst.*, 1901 (2), 122; P. Breuil, *Jour. Iron and Steel Inst.*, 1907 (2), 1; Burgess and Aston, *Trans. Amer. Electrochem. Soc.*, 1912, 22, 244; D. M. Buck, *Jour Ind. and Eng. Chem.*, 1913, 5, 447; *Jour. Ind. and Eng. Chem.*, 1916, 8, 209.

§ *Jour. Iron and Steel Inst.*, 1916 (1), 48.

|| *Jour. Iron and Steel Inst.*, 1907 (2), 103.

¶ Friend, *Corrosion of Iron and Steel*, p. 321.

855. Protection of Iron from Rusting.—It is evident from the electrolytic nature of corrosion that the rusting of iron may be prevented by keeping it from contact with electrolytes, by rendering the iron " passive," or by making it cathode, the last being accomplished by contact with a more positive metal such as zinc, or by the application of an external E.M.F.

The first method is carried out by painting, enameling, covering with another metal, or forming on the surface of the iron by chemical action a coat of oxide or other compound. For success by this method it is necessary that the coating be impervious to moisture, and remain unbroken. These are difficult conditions to fulfill, particularly when the object is exposed out of doors and subjected to wear. Paints soon lose their insulating power, and are readily scratched, enamels become chipped, electro-plate usually contains thin spots which soon wear through, and the compounds formed in the Bower-Barff and other similar processes must be kept so thin in order to prevent chipping and peeling, that their serviceability is less than if they could be given a considerable thickness. The subject of rust-resisting paints is receiving much attention from the technical societies interested, and marked improvements are to be expected. At first sight it might seem that coating iron with a less corrodible metal, either by dipping it in the melted metal or by electro-plating, should be a perfect remedy for rusting; but experience has shown that of all the metals so applied to iron, only zinc or cadmium affords satisfactory protection, and when exposed to a good electrolyte like sea water even zinc fails to protect for more than a year or two. In coating by dipping, the thickness of the coating is limited, and only metals and alloys of low melting-point can be used. Galvanized iron, tin plate, and terne plate, the latter consisting of iron coated with an alloy of lead and tin, are made in enormous quantities by this method, but the durability of the last two is hampered by the corrosion induced by " local action " between the coating and the iron whenever the latter becomes exposed. In protecting iron by electro-plating there is a much wider choice of materials than in the dipping process, and theoretically the coating may be made of any thickness desired, but in practice its thickness is restricted by the increasing roughness of thick deposits and their liability to peel. For these reasons, coupled with the cost of producing heavy deposits, commercial electro-plate is usually thinner than the heaviest coatings made by dipping.

856. Utilization of Passivity to Prevent Rusting.—Kier in 1790 observed that iron, after treatment with fuming nitric acid, had lost its power of precipitating silver from a solution of silver nitrate, in other words, that the iron had been rendered immune to corrosion by silver nitrate. Chromic acid and several other oxidizing agents have since been found to exercise a similar effect in preventing iron from reacting as usual toward many reagents. Attempts have been made to prevent rusting by rendering iron passive, but, unfortunately, passivity soon ceases after removal of the iron from the passivifying solution, and the presence of certain salts may entirely prevent passivity; for these reasons the utilization of passivity for preventing the rusting of iron is as yet very limited. Although small amounts of alkalies accelerate the corrosion of iron, a strong solution entirely prevents rusting, and this passivity of iron in alkaline solutions has been very successfully applied to the prevention of corrosion in boilers.* Certain pigments used in paint, e.g. the chromates, are often classed as "inhibitors" from their supposed effect in preventing rusting by rendering iron passive.

857. Protection by Contact with Zinc.—The protection of metals from corrosion by placing a piece of zinc in contact with them seems to have been discovered by H. Davy † in 1824, and was first applied by him to prevent the corrosion of the copper sheathing of wooden ships. Since that time protection by contact with zinc has been applied to boilers and marine condensers, and plates of zinc are usually attached to the hull of steel vessels in the vicinity of bronze propellers, sea cocks, etc., which otherwise would induce serious corrosion of the steel in immediate contact with them.

The principle involved is that corrosion of a metal is lessened by the passage of current to it as a cathode, but there are two difficulties to be overcome in applying this method; first, a good electrical connection must be maintained between the two metals; and second, in some electrolytes a coating forms on a zinc anode which may lower its potential to such an extent that the protective action is entirely nullified. For the protection of copper and brass in sea water iron appears to be a better contact metal than zinc, in spite of the higher initial potential of the latter.

858. Prevention of Corrosion by Current from a Dynamo.—In the generation of current for plating the corrosion of zinc in primary cells long ago gave way to the dynamo, and in the prevention of corrosion in large boiler installations by cathodic action, voltaic action has recently been abandoned in favor of the dynamo. Wherever corrosion is severe such protection results in a very considerable saving in the cost of repairs, less interruptions in service, and a higher efficiency of boilers from prevention of the formation of scale. The method seems destined to a wide usefulness.

859. Corrosion of Non-ferrous Metals.—The observed behavior of the non-ferrous metals in regard to corrosion is in fairly good agreement with the principles set forth on page 793, modified by the formation of insoluble coatings upon them. The highly positive metals, aluminum and zinc, owe their durability entirely to the formation of an insoluble compound on their surfaces, and although durable in air, dissolve in all electrolytes which remove the protective coatings. Because of the high potentials of these metals, purity and freedom from "local couples" are especially important. Aluminum is corroded rapidly by the halogen acids, seriously by their salts, and vigorously by alkalies. Lead, tin, copper, brass, bronze, Munz metal, Monel, and silicon-iron alloys are the materials most depended on to withstand severe corrosive conditions when platinum cannot be used on account of cost, as in sea water, for conveying corrosive liquids, etc. Exclusion of oxygen, annealing to remove strains, and freedom from contact with more negative electrical conductors are highly important in minimizing corrosion. In neutral electrolytes brass is subject to the peculiar form of corrosion known as "dezincification," in which the zinc dissolves, leaving a skeleton of porous copper that is utterly lacking in mechanical strength.

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* F. Lyon, *Jour. Amer. Soc. Nav. Eng.*, 1912, 24, 845.

† *Phil. Trans. Royal Soc.*, 114, 151.

860. Corrosion by Stray Currents.—In addition to the chemical or natural corrosion to which metals buried in the earth are subject, any continuous length of metal, such as a water or gas main, or the lead sheath of telephone cables, may suffer from electrolytic corrosion. This may be so serious as to destroy in a single year a cast-iron water main that should normally have a life of 50 to 100 years, while the thinner service pipes may last only a few months in especially bad situations. This damage results from the practice of using the rails for returning to the power station the electric current used for operating street railways. A greater or less proportion of the total current flows from the rails through the soil to the pipes, follows the latter to the vicinity of the power station, where it returns to the rails once more in order to reach the negative terminal of the dynamo.

Whenever "direct current" leaves a metallic anode to enter an electrolyte the metal is liable to be corroded, the extent of such corrosion depending on the same principles which control the corrosion of anodes in the electro-plating and refining of metals. The most important factors in the corrosion of anodes are: the chemical nature of the particular metal or alloy which serves as anode, the amount of current flowing, the time, the nature, amount, and concentration of salts in the soil, the temperature, current density, and rate of circulation of the electrolyte. With alternating current corrosion is usually negligible in comparison with that produced by direct current. Faraday's and Ohm's laws are of fundamental importance in electrolytic corrosion. According to the former the amount of corrosion should be proportional to the current which leaves the anode, to the time, and to the chemical equivalent of the metal; the amount of current being determined by Ohm's law, that the current equals the electromotive force divided by the resistance.

Current which enters the system of pipes at different points throughout a city will leave the pipes in the vicinity of the power station. Two electrolytic cells are thus formed by the rails, earth, and pipes; one where current enters the pipes, in which the rails are anodes, and the other near the station, in which the pipes act as anodes, and are corroded. Although nothing is made public concerning corrosion of the rails, it is evident that this must occur to about the same extent as corrosion of the pipes, but will be distributed over a much larger area of the city. Soil conducts electricity only as an electrolyte, and by virtue of solutions contained in it, so that the resistivity of different soils varies greatly, as does that of the same soil under different conditions of moisture. Temperature is an important factor in the resistance of electrolytes, and when the ground is frozen to the depth of a few feet corrosion of the pipes by stray currents is at a standstill.

861. The Danger District.—This is the portion of the pipe system from which current flows into the earth on its way to the rails, and it may be located by taking measurements with a voltmeter between the rails and hydrants. Wherever the pipes are positive to the rails the former are in danger of corrosion; but a high voltmeter reading at one place does not always mean a greater flow of current than a smaller reading elsewhere, for the voltmeter reads only the IR drop produced by flow of current in the earth, and there is the possibility that in a soil of high resistivity a small current may produce a greater fall of potential than is caused by a larger current which flows in a better-conducting soil.

862. Extent of Corrosion.—The amount of current flowing in a single pipe has been found to vary from a few amperes to several hundred, and in the case of "bonded pipes" in some of the largest cities, to several thousand amperes. Faraday's law predicts the dissolving of 15 pounds of iron by one ampere flowing from the metal 18 hours a day for a year, which leads one to wonder, not that damage to the extent of hundreds of thousands of dollars is caused annually by stray currents, but that any pipes remain undestroyed. The discrepancy between the amount of current known to be carried by pipes, and the relatively slow rate of their destruction, has given rise to much controversy and misunderstanding. The dissolving of 15 pounds of iron per ampere-year is for a current efficiency of 100 per cent, and requires that the entire current be spent in dissolving iron, and none of it employed in liberation of oxygen at the anode. Experience with plating and refining solutions has shown that the current efficiency of anode corrosion is greatly affected by the current density (number of amperes per sq. foot of anode surface), by the concentration of the electrolyte, and its rate of circulation,—low current density, high concentration, and rapid circulation tending toward a high efficiency, and vice versa. While the exact current density and the concentration of the electrolyte is unknown in the corrosion of underground pipes, the extreme dilution and stagnation of the average electrolyte in the soil of city streets should lead to a low efficiency of anode corrosion, except where the bad practice of applying salt to switches to thaw ice has been indulged in.

863. Corrosion at Low Voltage.—The statement is often made that the voltage between pipes and rails must exceed the E.M.F. of decomposition of water (1.7 volts) before corrosion can occur. This is an error. It is only with insoluble electrodes, if both are of the same metal, that this voltage is necessary for the passage of current; with a soluble anode any voltage, however small, will cause some current to flow. No fixed value can be given for polarization (the counter E.M.F. caused by products of electrolysis) that will apply to stray-current corrosion in general; this varies from 0.01 to 2.0 volts, according to the current density, and the material, concentration, and freedom to circulate of the electrolyte,—factors which are difficult to determine in electrolysis of pipes buried underground.

864. Joint Electrolysis.—A peculiar form of corrosion sometimes occurs in water pipes, known as joint electrolysis. The average lead joint in water mains has a very low resistance, so that no appreciable current is driven from the pipe at the joint; but when a joint of high resistance is encountered a considerable proportion of the current may pass from one section of pipe to the next by way of the soil instead of through the packing of the joint, causing corrosion on the anode side of the joint. Since this process is repeated at every bad joint, the damage done by a definite amount of current may be many times greater than in ordinary stray-current corrosion. Fortunately high-resistance joints are rather rare.

865. Remedies.—Because of lack of space it is only possible to mention some of the more important remedies that have been used or proposed for prevention of stray-current corrosion:

1. Lowering the voltage drop on the track by:
   (*a*) Better bonds.
   (*b*) Use of copper cables in parallel with the rails.
   (*c*) Insulated negative feeders attached to the track at suitable points.
   (*d*) Negative "boosters" to draw off current at desired points on the track.

2. Bonding of pipes near the station to the rails or to the negative terminal of the dynamo, so that current leaves the pipes by a metallic instead of an electrolytic conductor.

3. Insulation of the pipes from the earth.

4. Insulation at pipe joints.

5. Use of the double trolley, i.e. carrying the return current on an insulated overhead wire.

6. The use of alternating instead of direct current for the operation of street cars.

CHAPTER XXX

PAINTS AND VARNISHES

By O. A. Hougen [*]

866. Definitions.—In the broadest sense paints and varnishes include all materials which are applied to surfaces in a liquid or semi-liquid form and which dry to an adherent coating. The chief distinction between a paint and a varnish is that in the former a portion of the components, called the pigment, is suspended in a liquid, called the vehicle, which upon drying produces an opaque film; whereas a varnish consists of a nearly homogeneous solution which upon drying forms a transparent or translucent film.

867. The Necessity of Painting.—The chief purpose of painting and varnishing is to protect a surface against decay, corrosion and abrasion. In addition painting serves the purpose of decorating the surface by obscuring the original surface and presenting a fresh surface of the desired color; in varnishing the original surface is displayed to better advantage rather than obscured.

868. Requirements of Paints and Varnishes.—In order to fulfill these functions a paint or varnish film should possess the following properties: (1) It should be chemically inert toward the atmosphere or surface of contact. (2) It should be impervious to air and water. (3) It should possess good wearing qualities, that is, resist abrasion due to wear, handling or exposure to the weather. (4) It should possess sufficient elasticity to be unaffected by the expansion and contraction of the underlying material.

869. Paint Pigments.—A paint pigment consists of a finely ground solid material which is suspended in a vehicle such as linseed oil to render the paint film opaque and to impart the desired strength and appearance. This property of rendering a surface opaque is termed opacity. The hiding power of a paint is dependent both upon opacity and the thickness of the film. Pigments may be divided into three classes, (1) body pigments, those pigments which impart the proper strength, elasticity and wearing properties to the paint film, (2) color pigments, which are used primarily for tinting purposes and (3) extenders, which are added to re-enforce the paint film or to lessen the cost of the paint.

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Classification of Paint Pigments.—The *white* pigments include basic carbonate white lead, basic sulphate white lead, zinc oxide, lithopone, leaded zinc, titania. The *brown* pigments include Prince's metallic brown, burnt sienna, Vandyke brown, umbers and burnt ochre. The *red* pigments include red lead; the red ferric oxides, such as Indian red, Turkey red and Venetian red; the red color lakes such as permanent vermilion, helio fast red, and lithol red. The *blue* pigments include Prussian blue, ultramarine blue, cobalt blue. The *yellow* pigments include litharge, ochre, chrome yellow, zinc chromate and barium chromate. The *green* pigments include chromium oxide, green aniline lakes, zinc green and verde antique. The *black* pigments include lampblack, carbon black, bone black, charcoal black, acetylene black and graphite. The *bituminous* pigments are also black and include asphalt, coal tar pitch, wood tar pitch, gilsonite, grahamite, nanjak and elaterite.

Basic carbonate white lead is one of the oldest and most extensively used pigments. Its composition corresponds to the formula $Pb(OH)_2 . 2PbCO_3$. It is made by various processes chief among which are the Old Dutch and Carter. In the Old Dutch process perforated lead buckles are piled alternately between layers of tan bark in earthenware pots and covered with acetic acid. The lead acetate first formed is converted into the basic carbonate by the carbon dioxide developed by the fermentation of the tan bark. In the Carter process the lead is first finely atomized, then acted upon successively by acetic acid and carbon dioxide. The carbon dioxide is obtained from the purification of combustion gases.

Basic carbonate white lead is the only pigment which is used extensively without combination with other body pigments or extenders. It possesses excellent durability and greater opacity than any other white pigment except lithopone and titania. Upon wearing, the pigment flakes off evenly thereby presenting a roughened surface which lends itself readily to repainting. As a priming coat on wood it takes first rank. It does not stand up well in damp atmospheres such as along sea coasts and is darkened by sulphur containing gases due to the formation of black lead sulphide. The paint film is soft so that it readily becomes dirty and is not easily cleaned. To overcome these disadvantages basic carbonate white lead is mixed with other pigments such as zinc oxide and basic sulphate white lead and with extenders such as barytes, silica and asbestine. Admixture with other pigments and extenders tends to minimize the discoloration by hydrogen sulphide, produces a harder surface which is easier to keep clean, lessens the tendency to " chalk," and increases the life of the paint film. Basic carbonate white lead should not be used where sulphur-containing gases are prevalent such as around barns and out-houses.

Basic lead sulphate is made by subliming a mixture of lead sulphide ore with coal in the presence of air. The lead sulphide is converted into the basic lead sulphate which is filtered off in bags. This pigment should not be confused with the commercial lead sulphate which is a harmful paint pigment. Basic lead sulphate is rarely used alone but usually in combination with white basic carbonate white lead and zinc oxide. The pigment usually contains zinc oxide, which comes from the original ore. This pigment possesses excellent covering properties, is uniform in size and quality, withstands the action of hydrogen sulphide better than the basic carbonate and produces a hard impervious film, unattacked by salt water. For this latter reason it is used as an ingredient in marine paints.

Zinc oxide is made by two processes, the French and the American. In the former process metallic zinc is burned in a current of air and the sublimed zinc oxide is filtered off in bags. In the American process the zinc oxide is sublimed directly from a mixture of zinc ore with coke in an enclosed furnace. One of the original incentives in the development of this pigment is its non-poisonous nature compared to lead pigments. It is claimed that the French-process zinc oxide is whiter and of higher purity. Zinc oxide with linseed oil dries to form a hard, impervious film, which may be readily cleaned. For this reason zinc oxide is the chief pigment used in enamels. Zinc oxide reacts with hydrogen sulphide, but the effect is not visible.

When used alone a zinc oxide film has a tendency to peel off in patches and does not lend itself to repainting; in addition the hiding power of pure zinc oxide paints is low. To offset these disadvantages, zinc oxide is always mixed with other pigments and extenders. Admixture with basic carbonate white lead prevents the film from peeling and produces a better surface for repainting. In permanency of color and in durability zinc oxide paints take front rank. Even when admixed with extenders and other pigments zinc oxide paint films retain their glossy surface and still repel dirt and water.

Lithopone consists of barium sulphate chemically combined with zinc sulphide. It is produced by the interaction of barium sulphide with zinc sulphate. The precipitate is heated to 500° C. then plunged into cold water, after which it is ground, washed and dried. This pigment has the greatest opacity of any of the common white pigments and hence is used where great spreading power is required, such as in painting interior walls which are not subject to great wear and weather exposure. Lithopone is discolored by sunlight and hence its use is limited to interior painting. The action of sunlight is to reduce zinc sulphide to metallic zinc. The white color is restored in the dark. The darkening of lithopone can be partially prevented by coating with zinc oxide; this, however, prevents the use of lithopone with rosin varnishes, a distinct advantage of this particular pigment. Lithopone is a chief constituent in interior flat wall paints.

floor paints and in cheap enamels. For outside work its use is limited to the priming coat only.

Leaded zinc pigments consist of mixtures of zinc oxide and basic lead sulphate produced in the same manner as American zinc oxide with addition of varying amounts of lead ores to the zinc ores.

Red lead is produced by first oxidizing lead to litharge and subsequently to red lead, Pb_3O_4. Red lead reacts very readily with linseed oil forming a lead soap which causes the oil to rapidly "liver." It is claimed that this is due to the presence of litharge, PbO. A red lead of this type should not be sold in paste form, but the dry pigment should be freshly mixed with linseed oil just before using. This is considered a distinct disadvantage of red lead because hand made pastes are much inferior to those ground in the factory. To overcome this disadvantage there has been developed a type of red lead consisting of 98 per cent Pb_3O_4 which does not harden in the can when mixed with linseed oil as a paste.

Red lead is a body pigment used chiefly as a priming coat on structural steel and metal work. For this purpose it is one of the best pigments known. It produces an extremely hard and tough film, not easily penetrated by air and moisture and adheres firmly to the metal. It is extremely effective in protecting steel from corrosion. The paint is, however, very difficult to apply because of its extreme weight. To facilitate brushing there is a tendency to dilute the paint with oil below the safe limit, the paint should contain at least 25 pounds of red lead per gallon of oil (33 pounds is preferable). To facilitate the application of red lead and to insure a more uniform coating, red lead is often mixed with a high percentage of filler such as silica, and lampblack. This dilution also lessens the tendency of the paint to sag when applied to vertical surfaces. Red lead is also used as a priming coat on moving parts since it resists vibration better than other pigments. The use of red lead is restricted to the first coat because it is whitened by action with carbon dioxide of the atmosphere.

Toch * claims that *ferric oxide* pigments are equal to red lead in the protection of steel. The ferric oxide pigments, both natural and artificial are permanent in color, inert toward the atmosphere, and extremely opaque. *Tuscan red* is particularly resistant to temperatures up to 300° F. and to extreme exposure. It is used extensively for the painting of passenger cars, steam pipes, radiators, machinery and implements. Next to lithopone it is the finest pigment known. *Venetian red* consists of a chemically prepared mixture of ferric oxide and calcium sulphate. *Red clays*, naturally colored with ferric oxide, are used only as cheap adulterants.

Permanent vermilion, *helio fast red* and *lithol red* are pigment lakes. A *lake* is a dye which is absorbed upon the surface of an inert base such as barytes or clay. Lakes are used only for the purpose of coloring. The red pigment lakes have practically replaced the expensive mercury vermilion pigment.

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* Toch, *Chemistry and Technology of Paints*, p. 62, 2d edition.

Prince's metallic brown, is a body pigment, which is used extensively for painting tin roofs, barns and freight cars where good protection is desired for wood or steel at low cost and where beauty is of no consideration. This pigment is a native iron ore. It is highly opaque, fairly permanent in color and quite durable.

The bituminous pigments serve well in dark places but when exposed to sunlight break up into carbon, producing an "alligatoring" effect and permit the penetration of air and moisture. Bituminous materials, especially when mixed with linseed oil vehicle, have given excellent service in the protection of underground water pipes, and structural steel used in mine and tunnel construction.

870. Extenders.—The paint extenders include the various forms of barium sulphate, such as blanc fixe, barytes, heavy spar; the crystalline forms of silica, such as chert, quartz, sand and flint; the amorphous varieties of silica, such as fullers' earth, diatomaceous earth, etc.; the magnesium silicates, including asbestos and asbestine; clays; gypsum; artificial barium carbonate and the various forms of calcium carbonate, such as chalk, and marble dust.

Chemically prepared *barium sulphate* is the most extensively used filler, its characteristic property being extreme chemical inertness. It has practically no hiding power and hence serves chiefly as a diluent and as a base for the precipitation of the color lakes. The artificial product is finer and stays in suspension better than natural barytes. The *crystalline varieties of silica* are added chiefly to give "tooth" to the paint, that is ability to fasten to the underlying surface. The amorphous varieties are added to prevent the heavier pigments from settling out. The *magnesium silicates* are used in fireproofing paints and also serve the purpose of maintaining the heavier pigments in suspension. Asbestine serves as an excellent re-enforcement for paint films. *Clays* should never exceed 15 per cent because they reduce the wearing qualities of the paint film. Kaolin clay is best because of its purity.

871. Paint Vehicles.—The vehicles used in paints consist chiefly of a drying oil, often mixed with a thinner. Water serves as the vehicle in the so-called water paints. Drying oils consist of the glycerides of the unsaturated fatty acids. Upon drying they form a tough elastic solid film. This type of drying is caused by the absorption and chemical combination with oxygen of the air. In contrast with this type of drying is the familiar type caused by simple evaporation, as characterized by the drying of the vehicle thinners.

Linseed oil is the standard oil vehicle used in paint manufacture. Linseed oil is extracted from flax seed by various processes such as cold and hot pressing and solvent extraction. When the flax is grown for seed its stem is unserviceable as a textile fiber. The suspended impurities in linseed oil are known as "foots." These are removed by prolonged standing or centrifuging. The desirable constants of raw linseed oil are:

Specific gravity 15°-15° C.	.932° to .936°
Flash point (open cup)	240° to 250° C.
Fire point	290° to 300° C.
Drying on glass	3 to 4 days
Acid number	2 to 6
Saponification number	189 to 195
Iodine number	minimum 186
Refractive Index	1.4805 to 1.4790

The dried film of linseed oil is known as "linoxyn." This is the principal constituent by volume of all paint films and oil varnish films. In gloss paints linoxyn constitutes at least 66 per cent of the volume of the film, in flat paints the linoxyn may be below 50 per cent. *Stand oil* consists of a high grade linseed oil which has been bleached and "heavibodied" by prolonged heating at 600° F. No drier is added. The drying of linseed oil is accelerated by the process known as "boiling." This consists simply of heating the raw linseed oil and adding with continued heating various driers consisting of lead and manganese compounds.

Soya bean oil has served as an excellent substitute for linseed oil when prepared from certain varieties of the Soya bean, but the product is unreliable and tends to dry slowly.

China wood oil, also known as Tung oil, is particularly serviceable for waterproofing, for which purpose it is extensively used in varnishes. It dries to an opaque wax-like film in contrast to the transparency of linseed oil. Rosin can often be used to advantage with China wood oil.

Fish oil, particularly from the Menhaden, has been found suitable when used in conjunction with linseed oil. The particular objections to this oil are slowness of drying and objectionable odor. This oil gives satisfactory service in smoke stack paints and in zinc oxide paints in damp climates.

Other oils, such as *corn* oil and *pine* oil are of minor importance. *Perilla* oil has high drying properties but tends to form drops upon drying.

872. Thinners are a portion of the paint vehicle which are added to increase the spreading power of the paint, to facilitate application and to hasten drying. The thinner evaporates almost completely subsequent to its application and hence does not enter into the composition of the final paint film. Thinners also serve to increase the penetration of paint into wood and hence are always used in priming coats.

Turpentine is the standard paint thinner. It is a mixture of the various terpenes, obtained from the steam distillation of the resinous exudations of the pine tree, leaving rosin as a by-product. Turpentine is particularly valuable because of high solvent power, excellent flattening properties and ideal rate of evaporation.

Turpentine substitutes include other solvents such as benzol, petroleum spirits, and solvent naphtha.

873. Driers.—A Drier constitutes that portion of the paint vehicle which is added for the purpose of hastening the drying of the oil. Driers usually consist of the resinates of lead and manganese. Crusher's drier is prepared by heating the oxides of lead and manganese in linseed oil to form a concentrated solution. This concentrated solution is later incorporated into raw linseed oil in the ratio of 1 part to 16 parts of raw linseed oil by prolonged heating. The final product is known as " boiled " linseed oil.

Solid driers, consisting of lead and manganese compounds, may be added directly to raw linseed oil without heating, but the product known as " bung hole boiled oil " is unsatisfactory.

Lead and manganese resinate driers obtained from rosin are said to be satisfactory provided no excess rosin exists. The so-called *Japan driers* differ from the oil driers in being dissolved in turpentine rather than linseed oil.

874. Paints for Various Purposes.—The composition of a paint best suited for a particular service has been determined after years of practical applications on various types of construction and by means of the famous fence exposure tests wherein panels of wood and steel coated with paints representing a wide variety of compositions are exposed to the weather during many years of service. Such fence tests have been conducted by various paint manufacturers, educational institutions and the American Society of Testing Materials under widely varying climatic conditions. The results of such experiments have enabled manufacturers to recommend and produce the most suitable composition for a particular service.

Paints for Wood.—A mixed pigment paint is better than a single pigment paint for the protection of wood. In general this can be said of paints for all purposes. Good results are obtained with white lead combined with zinc oxide and a moderate amount of filler such as barytes, silica or asbestine. Tinted paints have proven most satisfactory from the standpoint of durability and maintenance of color. The durability of a paint depends largely upon the priming coat. This first coat should contain as high as 60 per cent vehicle, including a considerable proportion of thinner to increase the penetration of the paint into the wood, dissolve any resin in the wood and produce a better anchor for the succeeding coat. Paints containing oxide of iron, such as Prince's metallic brown, give excellent durability but are often objectionable because of color.

Barn paints are usually made from the poorer grades of iron oxide pigments, mixed with oils dissolved in turpentine substitutes. This does not signify that iron oxide pigments are inferior; in fact some of the most durable paints are made from Indian red and Prince's metallic brown. Ferric oxide itself is a very inert pigment; however, the natural products are far from uniform and often occur admixed with a high proportion of clay.

Enamel paints are used to give a high gloss surface. Enamels consist of a zinc oxide pigment ground in a varnish or heavy bodied linseed oil. Lithopone is usually used in conjunction with zinc oxide. As a priming coat a lithopone paint containing a high percentage of thinner is used. An egg shell finish may be obtained by polishing the surface with pumice. Dammar gum varnishes serve as excellent vehicles.

Flat Wall Paint.—The painting of interior walls is the most suitable finish from the standpoint of health and cleanliness. The glue accompanying the use of calcimine and wall paper permits bacterial growth, whereas oil paints destroy such organisms. The usual flat wall paints contain zinc oxide with an inert filler ground in a varnish thinned with turpentine. Lithopone is used because of its good hiding power, permitting two coats to suffice.

The chief objection to the use of calcimine is that it cannot be washed and is not as durable as an oil paint. *White wash* is the cheapest paint possible for interiors; its use is, however, restricted to rough interiors such as barns.

Paints for cement and concrete are necessary to prevent the dusting off of cement due to abrasion and also to protect the concrete from oil. Animal or vegetable oils have a tendency to make cement soft and crumbly. Linseed oil paints can not be used successfully on cement because of the destruction of the film by the free lime present in the cement. An oil containing a free resin acid to react with the lime has been found desirable. China wood oil containing a hard resin such as copal is frequently used. This combination gives excellent durability and water-proofing properties. In order to use regular linseed oil paints it is necessary to previously treat the cement surface with zinc sulphate to neutralize the free lime present.

Paints for Structural Steel.—Corrosion of iron and steel is due to electrolysis caused by the presence of air and moisture. According to the report of Committee D-1 of the American Society of Testing Materials * paint pigments are classified into three classes according to their effect on the corrosion of steel; those that inhibit the action of electrolysis presumably by rendering the metal passive, those that accelerate corrosion and those that are neutral.

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* Reports of the Committee on Preservative Coatings for Structural Materials, 1903-1913, Am. Soc. of Testing Materials.

Inhibitors	*Indeterminates*	*Stimulators*
Zinc lead chromate	White lead (quick)	Lamp black
Zinc oxide	Basic sulphate white lead	Blance fixe
Zinc chromate	White lead	Barium sulphate
Zinc barium chromate	Blue lead	Ochre
Zinc lead white	Lithopone	Carbon black
Prussian blue (inhibitive)	Orange mineral	Graphite No. 2
White Lead (Old Dutch)	Litharge	Barytes
Ultramarine blue	Red lead	Graphite No. 1
Willow charcoal	Venetian red	Prussian blue (Stimulative)
	Metallic brown	
	Whiting	
	Precipitated calcium carbonate	
	China clay	
	Asbestine	
	American vermilion	
	Chrome yellow	

Red lead has long been considered the best priming coat for structural steel. It produces a tough, elastic film impervious to air and moisture. Because of its great weight and poor spreading qualities there is a tendency to thin it down at the expense of its protective value. Recently the development of rust-inhibitive paints containing zinc and lead chromates have come into use, their high cost preventing their extensive application.

The problem of vehicle is also of importance in the protection of structural steel. It is generally conceded that a pure linseed oil priming coat is detrimental in that it stimulates corrosion. The presence of pigments greatly retard this corrosion. For this reason the priming coat should contain little oil. The linseed oil film is rendered more impervious by the use of a spar varnish.

The use of bituminous paints for the protection of steel has often been recommended; however, in general, such paints are unsatisfactory when exposed to sunlight, but serve excellently in the protection of underground pipes, tunnel and mine timbers.

Iron pipes may also be protected by the Angus Smith method, wherein the pipes are first coated with linseed oil and baked, then dipped into hot coal tar pitch, or coal-tar pitch admixed with linseed oil. Bitumens other than coal tar pitch may be used.

Small metal objects may be protected by a thick enamel, called *black Japan.* In this process the object is dipped into a hot solution of linseed oil containing a solid bitumen, and subsequently baked to a glossy finish.

Paints for Refrigeration Plants.—Most paints fail when used for the coating of brine pipes due to the action of ice and water. Paints developed for protection under these conditions consist of a pigment possessing inhibitive properties and a waterproof vehicle. One excellent formula contains red lead, zinc chromate, asbestine and willow charcoal ground in linseed oil containing 40 per cent of a high grade kauri gum. Another successful formula contains a good grade of asphaltum and gutta percha, the latter being perhaps the best waterproofing material known.

Fire Resisting Paints.—All oil paints and varnishes are combustible, due to the presence of the oil. The addition of asbestine and boric acid aid in rendering the paint film non-combustible. The latter forms a glaze which prevents access of air. However, no paint film will protect wood from an intense fire; the best it can do is to resist ignition by sparks.

Water paints are those in which water serves as the vehicle. *Whitewash* is essentially a suspension of slaked lime in water. Materials such as glue, flour, soap, casein, alum and sodium silicate are often added to increase the adhesiveness of the lime. Sodium chloride is added to preserve the organic binder. Whitewash is used chiefly for sanitary purposes on rough interiors, such as barns, stables and cellars. *Calcimine* consists of calcium carbonate suspended in water. Glue is added to increase its adhesiveness. Various color pigments are added for tinting purposes Calcimine is used chiefly for the interior decoration of plastered walls.

875. Preparation of Surfaces for Painting and Application of Paint.—Usually all paint manufacturers furnish complete specifications for the method of applying their paints to various surfaces, and also for preparing the surface for painting. These specifications should be rigidly followed.

All surfaces should be thoroughly cleaned and dried before painting. The paint should be applied in dry weather and never when the temperature is below 40° F. In preparing wood surfaces for painting, all knots and sappy portions should be previously shellacked. In case the sap is excessive it should be scraped off and the surface touched up with red lead. The priming coat should always contain a high percentage of turpentine or other thinner to dissolve the wood resin, to increase the penetration of the pigment and to provide a flat surface for the succeeding coat. Each succeeding coat should contain a smaller proportion of thinner, the final coat containing only linseed oil as the vehicle. At least three coats of paint should be applied to all wood surfaces. For priming cypress one half pint of benzol should be added to each gallon of paint; for priming pine, one half pint of turpentine should be added. After priming, all cracks and nail holes should be filled with putty. At least three days should elapse between succeeding coats.

Before repainting old wood work, all dirt, soot and loose scales should be removed by scraping or sandpapering. Cracks and holes should be puttied. In some cases it may be necessary to remove the old paint entirely by means of a blow torch or chemical paint remover; the latter usually consists of a mixture of wood alcohol, benzol and acetone, a suitable ratio being 4 : 5 : 1.

In preparing *steel surfaces* for painting, all loose scales and rust should be thoroughly removed by the use of hammers, scrapers and wire brushes. Grease should be carefully removed, with benzine. It is important that all rust be removed, because it acts as a stimulator to further corrosion. It is also necessary that the surface be absolutely dry. The priming coat should be applied in the shop before assembling and while under cover. No thinner should be used in the priming coat, and a minimum of linseed oil consistent with fair working qualities. All rivet and pin holes should be painted; bolts should be dipped in the paint. Parts which are to overlap should be painted before riveting together. All scars produced during transportation and assembling should be touched up again with the priming coat.

In repainting old work the same precautions must be followed in providing a clean surface. All bare spots should be cleaned and retouched with the priming coat.

Before painting *plaster* the surface should be brushed with a solution of zinc sulphate in water, and all cracks filled with plaster of Paris. The first coat should consist preferably of a zinc oxide, lithopone pigment. In repainting old work, all grease must be removed with benzine, and entire surface washed with soap and water. Before applying calcimine it is necessary to size the walls; this consists in brushing on a hot solution of glue.

In preparing *cement* and *concrete* for painting, all grease and oil should first be removed with benzine, and the surface brushed with a solution of zinc sulphate to neutralize the lime. The first paint coat may consist of 10 pounds of white lead per gallon of linseed oil, using no drier. After the priming coat any paint desired may be used.

876. Varnishes may be classified into two groups, the oil varnishes and the spirit varnishes. Oil varnishes consist of a resin dissolved in linseed oil which upon drying produces a tough, elastic film. In spirit varnishes the resin is dissolved in a volatile solvent such as benzol or alcohol, which upon drying evaporates and leaves a flat surface of the resin.

877. Resins.—The natural exudations of trees, particularly the conifers, are known as gums and resins. Gums may be distinguished from resins in being partly soluble or gelatinizable in water and insoluble in alcohol, whereas resins are insoluble in water but soluble in turpentine, alcohol and benzol, especially after heating. The true gums are not used in varnish manufacture. When resins contain a considerable quantity of the naturally occuring essential oil they are known as oleo-resins or balsams. When such resins have been allowed to accumulate on the ground with evaporation of the essential oils, they are called fossil resins. When mixed with mucilaginous matter they are known as gum-resins. The resins used in varnish manufacture may be classified into (1) natural resins; (2) rosin, also known as colophony; (3) shellac, and (4) synthetic resins.

The *natural resins* include all the naturally occurring resins which are used in varnish manufacture. These may again be subdivided into those which are partly soluble in alcohol and hence may be used in spirit varnishes, such as anime, dammar, dragon's blood, elemi, mastic and sandarac. Anime is used to impart additional toughness to varnish films, and dragon's blood is prized because of beautiful coloring properties. The second subdivision of the natural resins include those which are soluble in turpentine and linseed oil only after heating. These include all the fossil resins, such as amber, and the copals, such as Angora, Demarra, Java, Manila, Pebble, also Kauri and Zanzibar. The older a resin the more suitable it is for varnish making, in that it provides a harder and more lustrous surface. Kauri and Zanzibar are the most valuable resins in varnish manufacture. Amber is rarely used because of its high cost. An increase in resin produces a harder and more glossy finish, but the toughness of the film is reduced.

Rosin is the residue left after the distillation of turpentine from pine tree resin. It contains considerable free acid, which is often neutralized by the addition of lime. Hardness may be increased and acidity decreased also by heating. In general, rosin is considered as a cheap and inferior adulterant in linseed oil varnishes because it renders the film very brittle, turns white when water is applied and imparts poor wearing qualities. With China wood oil, however, rosin produces an excellent varnish, durable and highly water-proof.

Shellac is a product of lac which is a secretion of an insect that feeds upon the resinous exudation of trees native to India. To produce shellac, the lac is heated in bags and when melted is squeezed through the cloth. Orpiment is added to give color to shellac. Rosin is added only as a cheap adulterant. Shellac is soluble in alcohol, hence is used in spirit varnishes. It is insoluble in benzine, turpentine, water and acids. Shellac is often bleached with sodium hypochlorite. Bleached shellac becomes insoluble in alcohol upon storage.

Synthetic resins include such materials as Bakelite and cellulose nitrate which are used in spirit varnishes.

878. Oil Varnishes are made by melting resins at as low a temperature as possible, adding hot linseed oil; and, after cooling slightly, the desired thinner, such as turpentine, is added. Oil varnishes are classified according to color, resistance to wear and luster. A " short " oil contains from 5 to 11 gallons of oil per 100 pounds of resin; a " long " oil from 25 to 50 gallons. A high resin content increases the luster and hardness but decreases the toughness of the varnish film. " Short " oil varnish is used where high luster is desired and where great resistance to wear is not required, such as on wood trim and furniture. " Long " oil varnish is used where durability is the chief requirement such as on floors and spars of ships; hence called

" spar " varnish. " Hard oil " finish is a cheap grade of rosin varnish often used for interior house-finishing. " Gloss " oil varnish is the cheapest grade of varnish made; it consists of rosin dissolved in benzine. Floor varnishes usually contain from 15 to 18 gallons of oil per 100 pounds of resin. Tung oil has been extensively used for this purpose because of its water-resisting properties.

Baking varnishes include those varnishes which are baked upon the surface at the highest permissible temperature. Baking produces a hard impervious luster of high durability. Driers and rosin should not be used in this type of varnish.

Baking Japans are a type of baking varnish wherein part of the resin is substituted with asphaltum. This also provides a highly lustrous surface, resistant to wear and chemical action.

879. Spirit Varnishes are used chiefly for staining wood to enhance its beauty. An oil varnish is usually subsequently applied. The resins used in spirit varnishes include shellac, dammar, elemi. Lacquers and stains may also be included as spirit varnishes, although opaque pigments may be added as well as a drying oil. Spirit varnishes are also applied to metals to prevent chemical corrosion and oxidation by the air.

880. Testing of Paints and Varnishes.—The durability of paints can be tested only by long time exposure, such as by fence panel tests. The engineer should buy his paint upon specification or accept the recommendation of the paint manufacturer as to the most suitable composition. When paints are bought upon specification the actual composition may be checked by chemical analysis. The pigment and vehicle are separated and are analyzed separately. A chemical analysis is made on the pigment. Microscopic examination assists in the identification of adulterants. The vehicle is tested for quality of drying oil, percentage and nature of thinner and nature of drier.

The chemical analysis of varnishes is highly uncertain and indefinite because of the extreme alteration of the resins and oil during manufacture. A few simple practical tests will reveal much as to the quality of the varnish. The time of drying can be noted by applying a thin coat of the varnish on a panel of wood previously painted black. The rubbing properties can be determined by polishing with steel wool and pumice after drying is complete. The luster and color can be compared upon applying a second coat to the panel. A varnish to be resistant to water should not turn white when a stream of cold water is run on the panel overnight. A similar test should be performed with hot water for thirty minutes. By applying a coat of varnish to a vertical glass surface and then peeling off with a knife five days later, the elasticity of the film will be indicated. A dry film of varnish which chalks when rubbed with the fingers indicates rosin.

For detailed information on the manufacture of paints and varnishes, the best approved specifications and methods of testing the following references will prove valuable:

REFERENCES

Technology of Paints and Varnishes by A. H. Sabin—Wiley and Sons.

Corrosion and Preservation of Iron and Steel by Cushman and Gardner—McGraw-Hill Company.

Chemistry and Technology of Paints by Maximilian Toch—D. Van Nostrand Co.

Analysis of Paints by Gardner and Schaeffer—McGraw-Hill Book Co.

Circular 69, Paint and Varnish, United States Bureau of Standards.

Reports of Committee on Protective Coating for Structural Steel, 1913, Proceedings of the American Society of Testing Materials.

CHAPTER XXXI

CONSTITUTION OF SOME OF THE MORE IMPORTANT NON-FERROUS ALLOYS *

BY R. A. RAGATZ †

881. General Principles.—In the following pages on the constitution of non-ferrous alloys, it is assumed that the reader is thoroughly familiar with the simple constitution diagrams discussed in Chapter XX. In addition, the following two rules ‡ will assist greatly in the interpretation of a constitution diagram, and in determining from the diagram, the transformations that take place when an alloy of known composition is heated or cooled through certain temperature ranges.

Rule 1. To determine the composition of the two phases present at any temperature when in a field where two phases are indicated, draw a temperature horizontal through the field. The compositions corresponding to the two points where this horizontal cuts the boundaries of the field will give the compositions of the two phases present. For example, referring to Fig. 1, which is the constitution diagram for the copper-zinc alloys, consider an alloy composed of 60 per cent copper and 40 per cent zinc. According to the diagram, if this alloy is at a temperature of 700° C., it will consist of two phases, α and β, both of which are solid solutions. At 700° C., the composition of the α solid solution is given by the point k, which is the intersection of the 700° C. horizontal with the line aka_1. The composition of the β solid solution at the same temperature is given by point n, which is the intersection of the 700° C. horizontal with the line bnb_2. This rule of course applies only to fields on the constitution diagram where two phases are indicated.

Rule 2. To determine the relative proportions by weight of the two phases present at any given temperature when in a field where two phases are indicated, draw a temperature horizontal, and note where it intersects the boundaries of the field. The ratio of the weights of the two phases is equal to the inverse ratio of the distances from the vertical corresponding to the average composition of the alloy, to the boundaries of the field.

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* References: Guillet and Portevin, *Metallography and Macrography*. Gulliver, *Metallic Alloys*. Hoyt, *Metallography*, Vol. II.

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‡ Similar to rules given by Hoyt, *Metallography*, Vol. I, p. 12–13.

For example, referring again to Fig. 1 and considering an alloy containing 60 per cent copper and 40 per cent zinc, at 700° C.,

$$\frac{\text{Weight of } \alpha}{\text{Weight of } \beta} = \frac{mn}{km}.$$

This rule also applies only to fields on the diagram where two phases are indicated.

Another point that should be understood is that the constitution diagram tells what constituents are present in an alloy at any temperature, only if the conditions are such that the alloy is in perfect equilibrium. Usually, if cooling is rapid, equilibrium will not be established, and reactions which would take place if the cooling rate were very slow, will not have an opportunity to proceed or go to completion.

882. The Copper-Zinc Constitution Diagram.* —The portion of the copper-zinc constitution diagram shown in Fig. 1 covers the composition range of alloys in this series which are of commercial importance. This diagram is of particular interest since it applies to the ordinary brasses, which are the most important non-ferrous alloys.

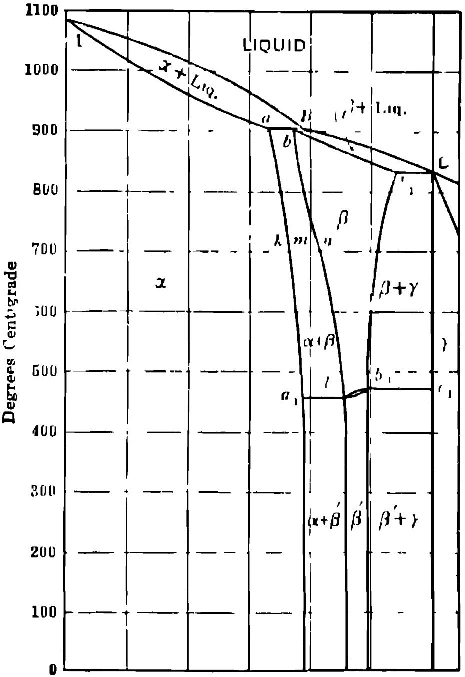

FIG 1.—Part of the Constitution Diagram for Copper-Zinc Alloys.

883. Solidification of Copper-Zinc Alloys.—When alloys between *A* and *B* in composition cool from temperatures within the liquid field, crystals of α solid solution start to form at temperatures indicated by the line *AB*. For alloys whose compositions are between *A* and *a*, solidification proceeds exactly the same as in any solid solution alloy, as described in detail in Art. 632. Solidification is complete at temperatures indicated by the line *Aa*, and the entire mass then consists of homogeneous α solid solution. In alloys between a and B in composition, solidification proceeds as in any solid solution alloy until the temperature horizontal abB at 904° C. is reached. At this temperature, the following reversible reaction takes place, in the direction indicated by the upper arrow. α (composition a)+liquid (composition B)$\rightleftarrows\beta$(composition b). If the composition of the alloy is between a and b, all of the liquid is used up in the reaction, and solidification will be complete at 904° C. If the composition of the alloy is between b and B, all of the α solid solution is used up in the reaction, and solidification will not be complete. The alloy will be composed of β solid solution of composition b and liquid of composition B, after the reaction at 904° C. has gone to completion. The temperature will then commence to drop, and solidification will proceed as in any solid solution alloy. Solidification is complete at temperatures indicated by line bb_1, and the entire mass will then consist of homogeneous β solid solution.

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* Roberts-Austen, *Proc Inst Mech Eng*, 1897, p. 31; Shepherd, *Jour. Phys. Chem.*, Vol. 8, p. 421; Carpenter and Edwards, *Jour. Inst. Metals*, Vol. 5, p. 127. Hudson, *Jour. Inst. Metals*, Vol. 12, p. 89; International Critical Tables, Vol. II, p. 435.

The solidification of alloys between B and b_1 in composition is similar to that of any solid solution alloy. Line BC indicates the temperatures at which solidification commences on cooling from temperatures within the liquid field. Solidification is complete at temperatures indicated by line bb_1, and the entire mass consists of homogeneous β solid solution.

884. Transformations in Copper-Zinc Alloys after Solidification.—Alloys whose compositions are between A and a consist of homogeneous α solid solution immediately after solidification, and cooling to room temperature causes no transformations.

Alloys between a and b in composition, will consist of α of composition a and β of composition b immediately after solidification. On cooling through the $\alpha+\beta$ field, the quantity of α will increase with consequent decrease in β, in accordance with Rule 2. At the same time, the compositions of the α and β are constantly changing, and may be determined at any temperature by applying Rule 1. If the vertical corresponding to the composition of the alloy intersects the inclined line aka_1, the β phase will disappear entirely at the temperature corresponding to the point of intersection, and the entire alloy will be composed of α solid solution.

Alloys whose compositions are between b and b_1 consist entirely of homogeneous β solid solution immediately after solidification. When alloys between b and b_2 in composition are cooled, α solid solution will start to separate at temperatures indicated by line bnb_2, and will continue to separate till the temperature horizontal a_1b_2 is reached. In a similar manner, alloys between b_1 and b_3 in composition will deposit γ solid solution in cooling between b_1b_3 and b_3c_1.

The transformations indicated by lines a_1b_2, b_2b_3, and b_3c_1 will next be considered. When alloys between a_1 and b_2 in composition are cooled to a temperature indicated by the horizontal line a_1b_2 (453° C.), they consist of an aggregate of two solid solutions, the α and the β phases. The α solid solution has the composition a_1 and the β solid solution has the composition b_2. The relative proportion of the α and the β phases depends upon the per cent zinc in the brass, and may be determined for any specific alloy by application of Rule 2. At 453° C., the α phase undergoes no change, but the β phase is bodily transformed into an allotropic modification, the β' solid solution. Alloys whose compositions lie between b_2 and b_3 undergo a progressive change from β solid solution into β' solid solution as the temperature drops between the two curved lines connecting b_2 and b_3. When alloys between b_3 and c_1 are cooled to a temperature indicated by the horizontal line b_3c_1 (470° C.), they consist of a mixture of two solid solutions, the β and the γ phases. The β solid solution has the composition b_3, and the γ solid solution the composition c_1. The relative proportions of the two phases in any specific alloy may be determined by application of Rule 2. At 470° C., the γ phase remains unchanged, but the β phase is completely transformed into β' solid solution.

885. Microstructure of Copper-Zinc Alloys.—According to the equilibrium diagram, all alloys whose compositions lie between A and a_1 will be homogeneous solid solutions at room temperature if cooled through the solidification range at a slow enough rate to maintain equilibrium conditions at all times. As a matter of fact, alloys in this range of composition when cast, cool too rapidly for equilibrium to be established. As a result, these alloys do not appear homogeneous when examined under the microscope, but will exhibit the dendritic structure as shown in Fig. 2. It is possible to produce a homogeneous structure in a cast brass by a prolonged anneal at approximately 700° C.

Brass sheets, rods, and tubing containing more than 63 per cent copper are cold worked to shape from the cast metal. The severe cold working causes distortion of the crystals making up the metal, and causes a great decrease in ductility, and an increase in hardness, tensile strength, and elastic limit. To prevent rupture, it is necessary to anneal the metal several times in the process of reduction to the desired shape. Though the material in the cast condition has the dendritic structure shown in Fig. 2, the cold working and annealing produce perfect homogeneity. Fig. 3 is a photomicrograph of sheet brass containing 70 per cent copper. The metal is composed of irregular shaped crystals which are homogeneous in composition. It should be noted that many of the crystal grains are crossed by parallel lines or bands. This effect is known as twinning, and is characteristic of α brass which has been cold worked and then annealed.

If the copper content is less than a_1, 61 per cent, a new constitutent makes its appearance. Fig. 4 shows the structure of Muntz Metal (60 per cent copper) after etching with ammonia and hydrogen peroxide. The light elongated areas are β' solid solution, while the equi-axed grains that make up the balance of the metal are α solid solution. It should be noted that the relative coloration of the α and β′ depends upon the etchant employed, and may be the reverse of that shown in Fig. 4. Acid ferric chloride or chromic acid with hydrogen peroxide blacken the β′ and leave the α light, as illustrated by Fig. 2.

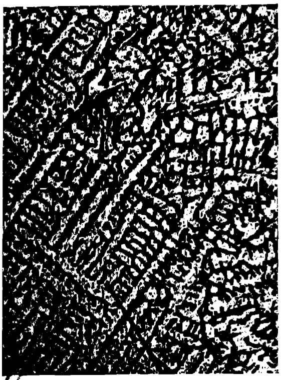

FIG. 2.—Cast Brass Containing 70 Per cent Copper and 30 Per cent Zinc. Dark areas of β with light dendrites of α. Etched with chromic acid and hydrogen peroxide. Magnification = 75d.

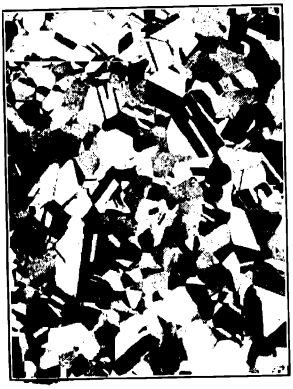

FIG. 3.—Sheet Brass Containing 70 Per cent Copper and 30 Per cent Zinc. Homogeneous α solid solution showing pronounced twinning. Etched with ammonia and hydrogen peroxide. Magnification = 75d.

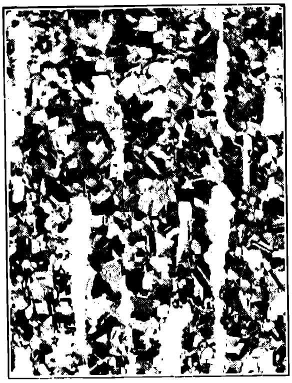

FIG. 4.—Muntz Metal Containing 60 Per cent Copper and 40 Per cent Zinc. Light elongated areas of β surrounded by small grains of α. Etched with ammonia and hydrogen peroxide. Magnification = 75d.

If the composition of the alloy is between b_2 and b_3, the entire mass will consist of homogeneous β′ solid solution at room temperature. The β′ solid solution differs from the α solid solution, in that the β′ never exhibits the dendritic structure characteristic of α brass in the cast condition nor the profuse twinning characteristic of α brass which has been cold worked and annealed.

886. Relation between Constitution and Mechanical Properties of Copper-Zinc Alloys.—The mechanical properties of the α and β′ solid solutions are quite different. Brasses consisting entirely of α solid solution are very ductile when cold, and rather soft, whereas a brass composed entirely of β′ solid solution is harder, has practically no ductility, and is so brittle that the tensile strength is low.

The α solid solution has maximum ductility at 70 per cent copper. Therefore, this is the most desirable composition if the brass is to be subjected to severe cold working in the reduction to the desired shape. However, brasses of lower copper content, 63 to 70 per cent, are often used even though they are worked with greater difficulty, since they are cheaper.

If the zinc content is above 39 per cent, the β′ constituent will be present.

The presence of the β' causes an increase in the tensile strength till the zinc content is approximately 40 per cent, above which the tensile strength drops off quite rapidly. The increase in tensile strength caused by the presence of a small quantity of β' and the decrease in tensile strength when the β' is present beyond a certain limiting value, is somewhat analogous to the effect of cementite upon the tensile strength of steel (Art. 679). The β' constituent causes a continuous decrease in ductility, and a continuous increase in hardness. Alloys containing less than 55 per cent copper contain so much β' that they are too brittle to be of any use.

The γ solid solution is very brittle, therefore any alloys containing this constituent are of little use.

887. Mechanical Treatment of Brass.—Since copper may be worked either hot or cold, it would be expected that the α solid solution low in zinc could be worked either hot or cold. This is the case if the zinc content is not above 10 per cent.

Brasses containing between 90 and 63 per cent copper cannot be worked hot, but must be reduced to shape cold. The most desirable composition from the standpoint of ease of working, is 70 per cent copper, but economic considerations often make it advisable to use a lower copper content, 63 to 70 per cent. If cold-worked brass is examined under the microscope, it will be seen that the grains are severely distorted and broken up.

The β' constituent is non-malleable at ordinary temperatures. Therefore, if a brass contains a considerable amount of the β' constituent, it must be worked hot. If only a small amount of β' is present, as in brasses containing 60 to 61 per cent copper, it is possible to cold work the metal if care is taken. However, brasses of such composition are usually worked hot.

The γ constituent is so brittle that an alloy containing it in appreciable quantities cannot be worked either hot or cold.

888. Heat Treatment of Brass.—It was shown that brass in the cast condition has a non-homogeneous structure. If the composition is above 61 per cent copper, the structure may be rendered homogeneous by a prolonged anneal at approximately 700° C.

The most important heat treatment which brasses are subjected to, is the annealing operation in the process of cold working to the desired shape. Cold working produces severe distortion of the grains making up the metal, and a great decrease in ductility, and an increase in hardness, tensile strength, and elastic limit. To prevent failure of the metal, it must be annealed several times in the course of reduction to the desired shape. Annealing causes recrystallization of the strained metal, and restores the ductility. The annealing temperature must be above a certain minimum, or recrystallization of the metal will not take place. The minimum annealing temperature is not fixed, but depends upon the amount of cold work the metal has been subjected to, and upon the composition. In general, the greater the amount of cold work the metal has been subjected to, the lower will be the minimum temperature required. For a given reduction in cross-section, the higher the zinc content, the lower will be the minimum temperature required. In annealing cold-worked brass, care must be taken that the annealing temperature is not too high, or the grain size will be large, causing brittleness. Specifications for brass sometimes require that the grain size be within certain limits. The microscope finds an important industrial application in controlling the annealing of cold-worked brass.

Inspection of the equilibrium diagram will tell at once whether the constitution and hence the mechanical properties of an alloy may be altered by quenching. The constitution of alloys containing 68 to 100 per cent copper is unaffected by quenching from temperatures below the line *Aa*.

If alloys whose compositions are between 61 and 68 per cent copper are heated within the $\alpha+\beta$ field and quenched, the β which was present at the quenching temperature will be retained due to the rapid cooling rate. Retention of the β causes an increase in the tensile strength, and a decrease in ductility.

889. Special Brasses.—The effect upon the microstructure and mechanical properties of brass produced by the addition of a third metal has been investigated by Guillet.* The addition of a third metal to a brass may affect the microstructure in one of the three following ways:

(1) The added metal does not alloy with the brass at ordinary temperatures, but exists in the free state dispersed throughout the mass. If an unetched section of brass to which lead has been added be examined under the microscope, numerous small globules of lead are seen distributed throughout the metal. In general, the presence of the additional constituent will cause a deterioration of the mechanical properties. The addition of lead to brass lowers the tensile strength and decreases the ductility, yet leaded brasses are very widely used because they machine so easily.

(2) The addition of a third metal causes the appearance of a new constituent. Both phosphorus and tin have this effect. In Naval brass (Art. 793) the addition of tin causes the appearance of a constituent similar to the δ constituent in the copper-tin series.

(3) The third metal added enters into solid solution, at least up to a certain limiting quantity. Some metals, as for example silicon and aluminum, affect the microstructure in the same manner as the addition of zinc. Certain other metals, as nickel and manganese for example, have the same effect upon the microstructure as the addition of copper. If the mechanical properties of an ordinary and a ternary brass which both exhibit the same

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* Guillet, *Comp. Rend.*, Vol. 140, p. 307, Vol. 142, p. 1047; *Rev. de Met.*, Vol. 2, p. 97, Vol. 3, p. 143.

microstructure be compared, it will be found that the mechanical properties of the ternary brass are superior.

890. The Copper-Tin Constitution Diagram.*—The copper-rich end of the constitution diagram, Fig. 5, is of interest since it is applicable to the ordinary copper-tin bronzes, which are of considerable industrial importance. The useful alloys in this series usually contain less than 25 per cent tin, therefore, the following discussion on copper-tin alloys will be confined to compositions ranging from 0 to approximately 25 per cent tin.

Fig. 5 is similar in many respects to the copper-rich end of the copper-zinc constitution diagram, hence it is unnecessary to give as detailed an account of the process of solidification of the copper-tin alloys, and subsequent transformations in the solid state, as was given for the copper-zinc alloys. Copper-tin alloys between a_1 and b_3 in composition when cooled to 500° C., will consist of α of composition a_1 and β of composition b_3. At 500° C., the β solid solution breaks up into an intimate mixture of α and δ, known as the $\alpha+\delta$ eutectoid. It should be noted that the right hand boundary of the $\alpha+\delta$ field curves quite sharply to the left between 500 and 300° C. Application of Rule 2 to this portion of the $\alpha+\delta$ field shows that the proportion of δ increases considerably as the alloy cools through this temperature range.

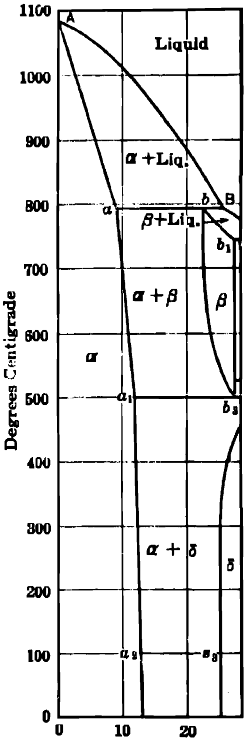

FIG. 5.—Part of the Constitution Diagram for Copper-Tin Alloys.

891. Microstructure of Copper-Tin Alloys.—According to the constitution diagram, alloys between A and a_2 in composition, 0 to 13 per cent tin, will consist of homogeneous α solid solution at room temperature, if the cooling rate was slow enough so equilibrium was maintained throughout the solidification range. However, bronzes within this range of composition when in the cast condition, exhibit a dendritic structure similar to that shown in Fig. 6, since cooling is too rapid for equilibrium to be estabished. If a cast bronze within this range of composition be annealed for an extended period of time, or successively worked and annealed, diffusion will take place within the metal, and a perfectly homogeneous structure will ultimately result.

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* Roberts-Austen and Stansfield, *Proc. Inst. Mech. Eng.*, 1895, p. 269, 1897, p. 6 Heycock and Neville, *Proc. Roy. Soc.*, Vol. 69, p. 320; *Phil. Trans.*, Vol. 189-A, p. 25, Vol. 202-A, p. 1; Shepherd and Blough, *Jour. Phys. Chem.*, Vol. 10, p. 630.

Alloys between a_1 and b_3 in composition, 13 to 25 per cent tin, will be composed of α and the $\alpha+\delta$ eutectoid immediately after the transition at 500° C. In cooling between 500° and 300° C., the amount of δ increases considerably, as indicated by the curved line bounding the right side of the $\alpha+\delta$ field.

892. Relation between Constitution and Mechanical Properties of Copper-Tin Alloys.—The α solid solution is more ductile and considerably stronger than pure copper. For rolled bronze, the addition of tin from 0 to 8 per cent causes a continuous increase in the ultimate tensile strength, elastic limit, hardness, and ductility.

The presence of the δ constituent increases the hardness, makes the metal more brittle, and decreases the ductility. At 18 per cent tin, the elongation is nearly zero. The ultimate tensile strength of cast bronze is increased by the presence of δ till the tin content is approximately 19 per cent, above which the tensile strength drops off rapidly.

The usefulness of the ordinary copper-tin bronzes for bearing metals is dependent upon the fact that the δ constituent imparts desirable anti-frictional qualities to the metal. Bronze containing above 11 per cent tin has the structure requisite for a bearing metal, since it is composed of hard particles of δ set in a relatively soft matrix of α. In general, the higher the tin content, and hence the proportion of δ, the greater will be the maximum bearing pressure at which operation will be satisfactory. However, as the quantity of δ increases, the brittleness and difficulty of working increase.

The usefulness of bronze as a material for gears is also due to the presence of the δ constituent. Bronzes containing 10 to 13 per cent tin have sufficient δ to give the gear the necessary strength and resistance to abrasion.

The compound Cu_3Sn is also brittle, and alloys consisting largely of this constituent find few applications in industry. Speculum metal (Art. 794) is composed largely of δ with some Cu_3Sn.

893. Mechanical Treatment of Copper-Tin Alloys.—The α solid solution may be worked cold, but cannot be worked hot unless the tin content is very low. The δ constituent decreases the ductility and embrittles the metal to such an extent that bronzes containing appreciable quantities cannot be worked cold. Cast bronzes containing 10 to 13 per cent tin are difficult to work, since the metal as cast is not homogeneous, but contains some δ.

The $\alpha+\delta$ bronzes can be worked hot if the temperature of the metal is between 500° and 800° C. In heating above 500° C., the $\alpha+\delta$ eutectoid is converted into β solid solution, which is considerably more malleable and ductile than the δ constituent. The working temperature should not exceed 800° C., since at this temperature the $\alpha+\delta$ bronzes undergo partial liquefaction. Bell metal, 75 to 80 per cent copper is usually cast to the desired shape in the manufacture of large bells, but in making small bells, the metal is sometimes worked to shape at a temperature between 500° and 800° C.

894. Heat Treatment of Copper-Tin Alloys.—The heterogeneous structure shown by cast alloys between A and a_2 in composition, 0 to 13 per cent tin, may be effaced by a prolonged anneal. Annealing causes an increase in the ductility, and a decrease in the hardness and tensile strength. Annealing cold-worked bronze causes recrystallization of the distorted metal, with pronounced twinning.

Inspection of the diagram will tell whether the constitution and hence the mechanical properties of an alloy may be altered by quenching. Alloys between A and a in composition will be unaffected by quenching at temperatures below the line Aa, provided that the structure of the metal was initially homogeneous. Alloys between a and a_1 in composition will be composed of α and β if heated to temperatures above the line aa_1 and then quenched. Alloys between a_1 and b_3 in composition will consist of α and β when heated above 500° C., and quenching will result in retention of the β solid solution. The mechanical properties of the β solid solution are superior to those of the δ solid solution, hence the mechanical properties of the $\alpha+\delta$ alloys are considerably improved by quenching at temperatures between 500° and 800° C. The ultimate tensile strength, ductility, and malleability are increased. It has been mentioned that small bells, which usually contain 20 to 25 per cent tin, are often worked to shape at temperatures between 500° and 800° C. An alternate method is to heat above 500° C., quench, and then work to shape cold. Retention of the β solid solution as a result of the quenching operation imparts sufficient malleability to the metal so it may be worked cold.

895. Special Bronzes.—Phosphorus, lead, zinc, and silicon are the most important elements that are alloyed with copper-tin bronzes to improve their properties.

(*a*) *Phosphor Bronzes.*—Phosphor bronzes may be divided into two groups, according to their phosphorus contents. (1) The finished bronze contains only a trace of phosphorus, and the improvement in mechanical properties is due simply to the deoxidizing action of the phosphorus. When bronze is melted, oxides of copper and tin are formed, and are a source of weakness in the metal. When phosphorus is added to the molten metal, the oxides of tin and copper are reduced, and the phosphorus pentoxide which is formed enters the slag on the surface of the metal. (2) Phosphorus is present in the finished metal up to approximately 0.4 per cent. In addition to acting as a deoxidizer, the phosphorus added to these bronzes affects the mechanical properties by the formation of the compound Cu_3P. This constituent is hard, brittle, has a low coefficient of friction, and resists abrasion. Phosphor bronzes of this class find their principal application in the manufacture of bearings and gears. The hard particles of δ and Cu_3P are set in a relatively soft matrix of α.

(*b*) *Lead Bronzes.*—If lead is present above 2 per cent, the tensile strength and ductility decrease quite rapidly. The presence of lead makes a bronze easier to machine, and also greatly improves the anti-frictional qualities of the metal. Leaded bronze for bearings may contain as high as 30 per cent lead. The lead is practically insoluble in the bronze, and exists in the free state dispersed throughout the metal. A difficulty encountered in the manufacture of high lead bearing bronzes is the tendency of the lead to segregate on cooling. It has been found that this difficulty may be overcome by rapid cooling, and by adding approximately 1 per cent nickel. Plastic bronze has approximately the following composition: 64 per cent copper, 5 per cent tin, 30 per cent lead, and 1 per cent nickel. In leaded bronze, the soft particles of lead are set in a hard matrix of bronze.

(*c*) *Zinc Bronzes.*—Zinc acts as a deoxidizer, increases the fluidity of the molten metal, and decreases the tendency of the metal to form blowholes. The zinc goes into solution, and has the same effect upon the constitution as the addition of copper. Fig. 6 shows the microstructure of a zinc bronze which is used quite extensively. Small light areas of the $\alpha + \delta$ eutectoid are surrounded by skeletons of heterogeneous α solid solution. If the zinc content is below 2 per cent, the mechanical properties are not greatly affected. If the zinc content is greater, the tensile strength and ductility drop off.

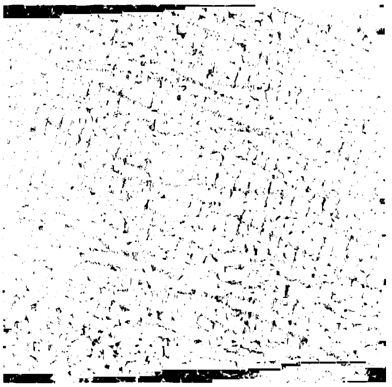

FIG. 6.—Government Bronze Containing 88 Per cent Copper, 10 Per cent Tin, and 2 Per cent Zinc. Small light areas of $\alpha + \delta$ eutectoid surrounded by skeletons of α. Etched with chromic acid and hydrogen peroxide. Magnification = 75d.

(*d*) *Silicon Bronzes.*—Silicon is added as a deoxidizer, and the finished product contains only traces of silicon. Silicon bronze finds its most important application in the manufacture of wire to be used for electrical conductors. It has a greater conductivity than phosphor bronze.

896. The Copper-Aluminum Constitution Diagram.*—In the copper-aluminum alloy series, both the copper-rich and the aluminum-rich alloys are of industrial importance. The portions of the copper-aluminum constitution diagram shown in Fig. 7 cover the composition range of the useful alloys in this series. Since the alloys of commercial importance contain 0 to 12 per cent copper, and 88 to 100 per cent copper, detailed discussion will be confined to these ranges of composition.

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* Curry, *Jour. Phys. Chem.*, Vol. 11, p. 425; Carpenter and Edwards, *Proc. Inst. Mech. Eng.*, 1907, p. 57; Gwyer, *Zeit. Anorg. Chem.*, Vol. 57, p. 113; Andrew, *Jour. Inst. Metals*, Vol. 13, p. 249; Merica, Waltenberg, and Freeman, *Bur. Stnds. Sci. Paper* 337.

The copper-rich end of Fig. 7 is quite similar to the other two diagrams which have already been discussed in this chapter, therefore a detailed account of the process of solidification and transformations in the solid state will not be necessary for the copper-rich alloys in this series.

897. Copper-Rich Alloys of Aluminum and Copper. — (*a*) *Microstructure.*—Alloys between 91 and 100 per cent copper will be composed entirely of homogeneous α solid solution at room temperature, if the rate of cooling during solidification was slow enough so that equilibrium was maintained. Cast alloys within this range of composition exhibit the heterogeneous structure which is characteristic of most solid solution alloys in the cast state.

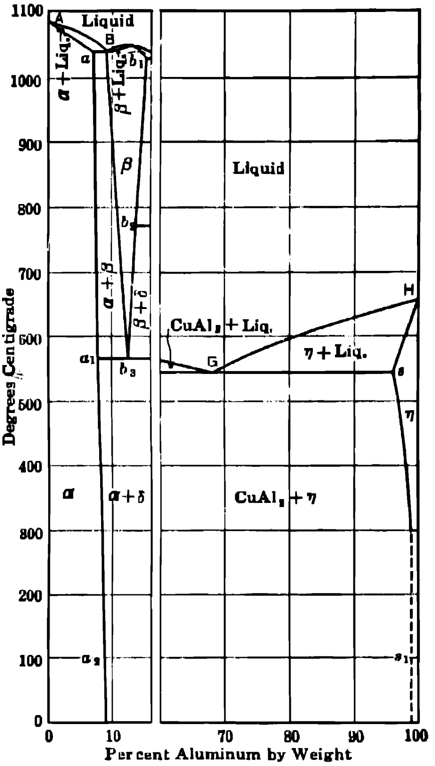

FIG. 7.—Part of the Constitution Diagram for Copper-Aluminum Alloys.

At room temperature, slowly cooled alloys between a_1 and b_3 in composition will consist of crystals of α mixed with the $\alpha+\delta$ eutectoid. The relative proportions of the free α and of the eutectoid are dependent upon the composition of the alloy. The quantity of eutectoid varies from 0 to 100 per cent as the composition varies from a_1 to b_3. The eutectoid assumes a coarsely granular form if any free α is present in the alloy, which is the case for compositions between a_1 and b_3. If the alloy has an aluminum content greater than b_3, the eutectoid tends to assume a finely laminated structure similar to pearlite in steel. Fig. 8 shows the structure of an aluminum bronze, in which the light areas of free α are mixed with the dark $\alpha+\delta$ eutectoid.

(*b*) *Relation between Mechanical Properties and Constitution.*—The α constituent is strong, ductile, and relatively soft. The tensile strength of the α solid solution shows a continuous increase as the aluminum content increases from 0 to 9 per cent. The ductility shows a maximum value at 7 per cent aluminum, above which the ductiiity drops off.

The δ constituent is hard and brittle. Its presence causes a continuous decrease in ductility and increases the brittleness. Its presence in small quantities causes an increase in tensile strength. At 10 per cent aluminum, the tensile strength has its maximum value, and drops off quite rapidly when this aluminum content is exceeded.

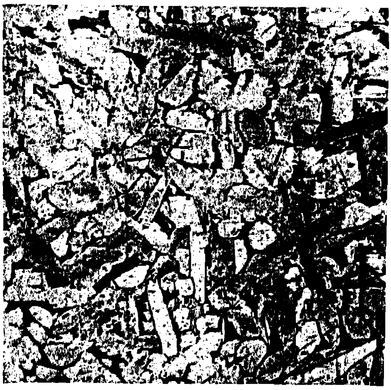

FIG. 8.—Aluminium Bronze Containing Approximately 91 Per cent Copper and 9 Per cent Aluminum. Dark areas of α + δ eutectoid surrounded by light α. Etched with acid ferric chloride. Magnification = 75d.

(*c*) *Mechanical Treatment.*—Alloys composed entirely of α solid solution may be worked either hot or cold. The presence of the δ constituent in appreciable quantities makes the alloys brittle, therefore alloys containing over 9 per cent aluminum cannot be worked cold. However, alloys containing 9 to 12 per cent aluminum may be hot worked between 566° and 1040° C. Heating above 566° C. converts the α + δ eutectoid into β, which may be worked hot.

(*d*) *Heat Treatment.*—The heterogeneous structure of cast alloys containing 91 to 100 per cent copper may be destroyed by annealing, or by mechanical work combined with annealing. Inspection of the constitution diagram will tell at once if it is possible to alter the constitution, and hence the mechanical properties, of an alloy by quenching. The constitution of alloys between A and a in composition, 0 to 7 per cent aluminum, is unaffected by quenching. If alloys between a and a_2, 7 to 9 per cent aluminum, are heated within the α+β field and quenched, the β constituent will be retained due to the rapid rate of cooling. When alloys between a_1 and b_3 in composition are heated above 566° C., the α + δ eutectoid is converted into β. If the alloy is then quenched, the β constituent is retained due to the rapid cooling rate. The quantity of β present in a quenched alloy depends upon the composition of the alloy and also upon the quenching temperature employed. For example, an alloy containing 12 per cent aluminum when quenched from above 566° C. may consist of α and β, or entirely of β, depending upon the quenching temperature employed. The β constituent in quenched alloys often exhibits a striated appearance, similar to martensite in steel. This seems to indicate partial decomposition of the β in spite of the quenching. The retention of the β constituent in a quenched alloy increases the tensile strength and elastic limit, but decreases the ductility and impact resistance.

898. Aluminum-Rich Alloys of Aluminum and Copper.—The aluminum-rich alloys of the copper-aluminum alloy series are useful because of their lightness, which is combined with a good degree of strength and ductility. These alloys find their most important application in the automobile industry. The light alloys of copper and aluminum which are of commercial importance usually do not contain over 12 per cent copper.

When alloys between G and H in composition are cooled from temperatures within the liquid field, η solid solution will start to deposit at temperatures indicated by line GH. If the composition is between H and s, and the rate of cooling is slow enough so that equilibrium is at all times maintained, the alloys will be completely solid at temperatures indicated by line Hs, and will then consist of homogeneous η solid solution. If the composition is between G and s, η solid solution will separate as the alloy cools between GH and the horizontal Gs at 545° C. At this temperature, the alloy consists of η of composition s, and liquid of composition G. The liquid solidifies at constant temperature to form an intimate mixture of $CuAl_2$ and η. Such an intimate mixture of two phases resulting from the solidification of a liquid is known as a eutectic.

Light aluminum casting alloys usually contain 5 to 12 per cent copper. When examined under the microscope, they are seen to consist of η solid solution mixed with the eutectic. The η constituent may be somewhat heterogeneous due to the fact that the metal was cast, and cooled rather rapidly. However, the heterogeneity is not very pronounced.

The line ss_1 slopes to the right, indicating that the solubility of $CuAl_2$ in aluminum decreases as the temperature drops. At the eutectic temperature, 545° C., the η solid solution can hold approximately 4 per cent copper in solution, while at 300° C., the η solid solution can dissolve only 1 per cent copper. It is this decrease in solubility that makes possible the heat treatment of duralumin, which is discussed below.

The η solid solution has properties similar to aluminum. It is malleable and ductile, and not much heavier than aluminum. The presence of the compound $CuAl_2$ causes an increase in hardness, but a decrease in ductility. The addition of copper to aluminum causes a continuous increase in the tensile strength of sand cast alloys, to approximately 14 per cent copper. At the same time, the ductility decreases continuously, till at 14 per cent copper the elongation is nearly zero. The mechanical properties of castings are affected to quite a marked degree by the cooling rate. The more rapid the cooling rate, the finer will be the structure as shown by microscopic examination. The finer structure is accompanied by increased tensile strength and ductility. Therefore, chill castings are superior to sand castings, and castings of small cross-section have better mechanical properties than those of greater cross-section.

Duralumin (Art. 803) is usually used when the finished object is to be worked to shape rather than cast. It may be worked to shape either hot or cold, but is usually worked while hot. Duralumin is remarkable because of the great improvement in mechanical properties which can be obtained by suitable heat treatment, and the peculiar manner in which this improvement takes place. If duralumin is heated to 500° C. and water quenched, the mechanical properties are about the same as if the alloy had been slowly cooled. However, on standing at ordinary temperatures, the hardness and tensile strength will start to increase, and after several days will reach maximum values considerably above those of annealed duralumin of the same composition.

Annealed duralumin will show particles of $CuAl_2$ imbedded in η solid solution. Some $FeAl_3$ will be present, since iron is always present in the commercial aluminum which is used in making duralumin. The quenched duralumin shows less $CuAl_2$ than does the annealed metal, since on heating to the quenching temperature, some or all of the $CuAl_2$ dissolves. The $FeAl_3$ does not dissolve on heating to the quenching temperature. No change in the microstructure of duralumin can be detected on aging after quenching.

899. Copper-Nickel Alloys.—Copper and nickel are soluble in one another in all proportions, both in the liquid and solid states. The constitution diagram for this series of alloys is therefore similar to Fig. 8, Art. 632. The curves giving the temperatures of initial and final solidification for these alloys rise continuously from the melting point of copper, 1083° C., to the melting point of nickel, 1452° C. In this alloy series, the only transformation after solidification is a magnetic transformation, which is not accompanied by a change in microstructure.

The copper-nickel alloys as cast have a heterogeneous structure, but may be rendered homogeneous by a prolonged anneal, or by mechanical work combined with annealing. The effect produced by cold working followed by annealing is very similar to the effect produced upon α brass when subjected to a similar treatment. The cold working distorts the crystals, and annealing causes recrystallization of the strained metal, with pronounced twinning.

Quenching has no effect upon the constitution of copper-nickel alloys. The non-magnetic state cannot be retained by quenching from above the magnetic transformation temperature.

Nickel silver (Nickelene or German Silver) is a copper-nickel alloy carrying considerable zinc. The composition is variable, but is usually within the following limits:* copper, 52 to 80 per cent; nickel, 10 to 35 per cent; zinc, 5 to 30 per cent. Alloys within this range of composition form solid solutions. The cast alloys exhibit the usual dendritic structure, which may be effaced by annealing, or by cold working followed by annealing.

Monel metal (Art. 791) is used to a considerable extent in making castings, and in this condition has a nonhomogeneous structure. Monel metal is also rolled into various shapes, either hot or cold. If rolled cold, the metal must be annealed several times in the process of reduction to the desired shape. The finished material in the annealed state is perfectly homogeneous, as shown in Fig. 9. The small oxide inclusions are characteristic of the microstructure of Monel metal.

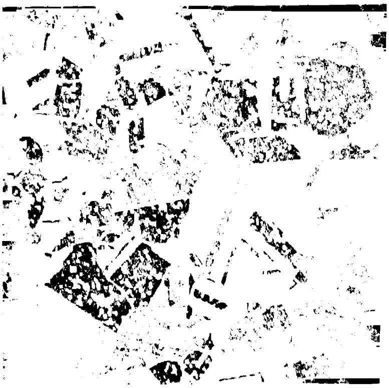

FIG. 9.—Rolled Monel Metal after Annealing. Shows homogeneous solid solution with twinning. Etched with acid ferric chloride. Magnification = 75d

900. Aluminum - Zinc Alloys.† — Aluminum-zinc alloys containing from 0 to 40 per cent zinc form homogeneous solid solutions. Since the alloys of commercial importance fall within this range of composition and hence are solid solution alloys, it is not necessary to give the constitution diagram for this series. These alloys when cast have the usual dendritic structure, which may be effaced by annealing or by mechanical work followed by annealing. Alloys containing up to 25 per cent zinc may be rolled hot, while alloys containing up to 15 per cent zinc may be rolled cold. However, the aluminum-zinc alloys are used mostly in the manufacture of light castings. An aluminum-zinc alloy containing 15 per cent zinc, 3 per cent copper, and 82 per cent aluminum is used for a light casting alloy to a great extent in Great Britain, in preference to the ordinary light aluminum-copper alloys which are used so extensively in this country.

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* *Bur. Stan. Circ.* No. 100.

† Rosenhain and Archbutt, *Proc. Inst. Mech. Eng.*, 1912, p. 319; *Bur. Stan. Circ.* No. 76.

CHAPTER XXXII

METALS FOR LIGHT-WEIGHT CONSTRUCTION

901. Properties Desired in Metals for Light-weight Constructions.—The modern advances in the use of light-weight construction in aircraft are gradually spreading to other methods of transportation and into other constructions. Automobiles are being gradually lightened and considerable reductions in weight have recently been made in trucks, buses, and in railway rolling stock. Buckets for excavation purposes, booms on derricks, floors for long-span bridges, engine pistons, housings, crankcases, and cylinder heads are other examples in the design of which attention has been sharply focused upon the desirability of reducing dead weight.

In estimating the usefulness of a material for light-weight construction the essential properties are a high ratio of elastic strength to weight, good stiffness, a proper degree of toughness, and low cost. If subjected to a range of temperature, the coefficient of expansion, the creep characteristics, the strength at elevated temperatures, and the thermal conductivity may be very significant qualities. Hardening capacity and the ability to retain hardness when subjected to attrition at high temperatures are sometimes necessary properties. Machinability, behavior under various types of forming operations, and weldability are other important considerations.

Some of the more valuable alloy steels, alloys, and cast irons which are used in high-strength constructions have been mentioned in Chapters XXIII to XXVIII. Herein the major properties of certain of the newer steels and alloys which find application in light-weight construction will be described. For a more extended discussion of the subject, the reader is referred to *Service Characteristics of the Light Metals and Their Alloys* in Rept. of Com. B-7, *Proc. A.S.T.M.*, 1934; *Symposium on High-strength Constructional Metals*, published by the A.S.T.M. in 1936; also a series of papers in *Proc. A.S.C.E.*, Vol. 62, Oct. 1936.

902. Low-alloy, High-yield-strength Steels.*—Since 1929 approximately a score of proprietary steels have been developed which have yield points in excess of 50,000 lb./in.^{2} These steels are also characterized by good ductility, toughness, and high endurance limit values. They have been recommended and used to an increasing extent for railway cars, engine frames, truck bodies, trailers, ships, bridges, pressure vessels, and oil-well casings. Most of these steels contain copper with additions of chromium or nickel. Since these low-alloy steels contain either copper and nickel or copper and chromium, they are much more resistant to atmospheric corrosion than carbon steels of comparable strengths, but not so resistant as the stainless steels or special alloys. A brief résumé of the physical properties of four steels of this group, Cromansil, Corten, Yoloy, and Hi-steel, follows. The moduli of elasticity values of these steels are between 29,000,000 and 30,000,000 lb./in.^{2}

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* See also paper by W. L. Collins and T. J. Dolan, *Proc. A.S.T.M.*, Vol. 38, Pt. 2, p. 157.

The Cromansil steels, in addition to the usual elements, contain chromium, 0.4 to 0.6, manganese, 1 to 1.4, silicon, 0.6 to 0.9 per cent, and carbon, 0.1 to 0.5 per cent in accordance with the properties desired. These steels when made with low-carbon contents are reported to be readily welded. Their tensile yield points vary between 45,000 and 90,000 lb./in.^{2} with ultimate strengths of 75,000 to 140,000 lb./in.^{2}, depending upon the thickness of the part and its composition.

Corten steels are low in carbon and carry silicon, 0.5 to 1.0, phosphorus, 0.1 to 0.2, copper, 0.3 to 0.5, and chromium, 0.5 to 1.5 per cent. As rolled, these steels exhibit tensile yield points of 50,000 to 60,000 and ultimate strengths of 65,000 to 75,000 lb./in.^{2} They are superior in ductility, toughness, and in resistance to corrosion to carbon steels of like yield points. The endurance limit is high, approximating 0.7 of the tensile strength. The steels are weldable and can be formed into shape either hot or cold.

Yoloy steels contain the elements present in steels of less than 0.25 per cent carbon plus nickel, 1.8 to 2.0, and copper, 0.9 to 1.2 per cent. These steels, as hot rolled, have tensile yield points of 50,000 to 70,000 lb./in.^{2} and tensile strengths of 70,000 to 98,000 lb./in.^{2}, depending on carbon content and thickness of piece. They are more ductile, tougher, more resistant to corrosion, and have better cold-forming properties than carbon steels of comparable strengths. Yoloy steels are said to be readily welded and have forging and hot-working properties similar to those of structural steel. The tenacity and yield point values for these steels can be raised considerably by heating at 900 to 950° F. for 4 to 5 hr., and excellent properties are obtainable by quenching and tempering.

Hi-steel is of low-carbon-steel composition with additions of copper, 0.9 to 1.2, nickel, 0.45 to 0.65, and phosphorus, 0.1 to 0.15 per cent. This steel, as rolled, has a tensile yield point of 56,000 to 69,000 lb./in.^{2} and a tenacity of 70,000 to 78,000 lb./in.^{2}, depending on thickness. Its endurance limit in reversed bending is about 0.7. In ductility, toughness, and resistance to corrosion it is superior to carbon steel of like yield point. Hi-steel is said to be easier to fabricate than carbon steel because of its high elastic ratio. It is also reported to be easily welded.

903. Corrosion-resisting Steels.*—At the outset it should be appreciated that there is no " noble " high-strength steel now known which is immune to all types of corrosion. Of the steels highly resistant to aggressive corrosive attacks, those alloyed with chromium and with chromium and nickel are the most resistant (see also Art. 731). Of these steels, the austenitic alloys are the most highly resistant to corrosion. They contain 17 per cent or more of chromium, half as much nickel, and small percentages of carbon, which, of course, must be in solid solution in the iron. The presence of carbides of iron, though forming the basis for effective hardening and tempering treatments, adds little to the chemical stability of the steel. Unfortunately solubility of carbon in the high-chromium alloys is limited to small amounts, usually less than 0.12 to 0.15 per cent. Hence the most resistant alloy steels cannot be strengthened by heat treatment, but their tenacity may be raised by cold work. These steels are made in electric furnaces. Their use has been steadily increasing during the past decade, and over 100,000 tons of corrosion-resistant steels are now being produced annually in this country.

Since there is a wide range in the severity of attack in different types of service, and since the high-alloy steels are expensive, many grades of these steels are manufactured, each for certain uses. Thus the A.S.T.M. specifies a 4 to 6 per cent chromium steel with low-carbon content and with or without 0.45 to 0.65 per cent of molybdenum or 0.75 to 1.25 per cent of tungsten for making coils for oil stills. Such steels have given satisfactory service in stills operating up to pressures of 1000 lb./in.^{2} and with effluent temperatures up to 930° F. These steels, when annealed, have tensile strengths of 65,000 lb./in.^{2} with yield points between 25,000 and 30,000 lb./in.^{2} and elongations of 30 per cent, or more, in 2 in.

For coal screens, pump rods, valve seats and stems, rods and hangers for gates for dams, steels of low-carbon content with chromium running from 12 to 15 per cent and small amounts of molybdenum or nickel have been used. In annealed state these steels are about 10 per cent stronger and 15 per cent less ductile than steel used for oil stills. The strength of these martensitic steels may be nearly doubled by cold rolling or more than doubled by heat treatment. Such steels will retain their tensile properties at temperatures up to 750° F. and are much stronger than carbon steels at temperatures up to 1200° F. They also have high creep resistance. At 1000° F. a stress of 13,000 lb./in.^{2} would be required to cause a creep of 1 per cent in 10,000 hr. Such steels can be welded but the weld should be annealed immediately to prevent air hardening.

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* For a more extended treatment of this subject, refer to an excellent paper *Corrosion-resisting Steels* by E. E. Thum, in Symposium on High Strength Constructional Metals, published by A.S.T.M. in 1936, from which much of the data here given were obtained.

Material suitable for turbine blades can be made from heat-treated steels of carefully controlled composition with 11.5 to 13.0 per cent chromium and not over 0.12 per cent carbon. Tests by N. L. Mochel show that such steels when quenched from 1750° F. exhibit nearly constant strengths of 170,000 to 180,000 lb./in.^{2} for drawing temperatures less than 900° F., with Johnson's apparent elastic limits approximating 100,000 lb./in.^{2}, and elongations of 15 to 18 per cent. Brinell hardness ranges from 420 to 370 as the drawing temperatures increase up to 900° F. The endurance limit in reversed bending is about half the tensile strength.

The most important high-strength, corrosion-resistant steel is the austenitic, so-called 18–8, which usually carries 18 to 20 per cent of chromium, 8 to 10 per cent of nickel, with silicon under 0.75 per cent, and carbon not above 0.12 per cent. Although expensive, the facts that it is stainless when exposed to domestic uses, industrial, seashore, and rural atmospheres, is highly resistant to corrosive acids, and is non-scaling in most furnace atmospheres at temperatures up to 1600° F. have led to an ever-increasing application of this very valuable steel. These steels must be cooled rapidly after prolonged heating at high temperatures to avoid carbide separation. They are non-magnetic, and after annealing exhibit tensile strengths of 80,000–85,000 lb./in.^{2} with proportional limits of only 20,000–25,000 lb./in.^{2} The percentage elongation in 2 in. is about 70 per cent and the Brinell hardness 145 to 160. The toughness is unusually high at all temperatures down to −400° F. When hard drawn, the tensile strength can be raised above 200,000 lb./in.^{2} with accompanying reduction in elongation to 5 or 10 per cent. Although the proportional limit of 18–8 is low, it has excellent creep resistance, requiring a stress of 17,000 lb./in.^{2} to produce a creep of 1 per cent in 10,000 hr. at 1000° F. Creep characteristics of several high alloy steels are shown in Fig. 1.

Since the 18–8 steels are close to the martensitic boundary, they precipitate carbides to the grain boundaries when subjected to prolonged heating at temperatures above 800° F. Such action produces susceptibility to intergranular corrosion. Preventive measures consist in increasing the chromium nickel content, or lowering the carbon, or in introducing either titanium or columbium to retain the carbon in the iron.

With low-carbon content, 18–8 steel can be welded. It is very difficult to machine unless alloyed with selenium or phosphorus. These steels have a thermal expansion coefficient about 45 per cent greater than carbon steels, a condition which must be allowed for when the two types are united in parts subjected to high temperatures. The 18–8 steels are said not to be highly resistant to certain types of stagnant chloride solutions or to sulphur-laden gases at high temperatures.

In addition to applications for utensils and equipment where stresses are low, the 18–8 steels in thin sections have been used for passenger car bodies, airplane parts, in high temperature equipment as in superpower plants, and in oil cracking. This material has also been used to surface the less expensive carbon steels in pressure vessels subjected to corrosion, also in ducts subjected to sewer gases.

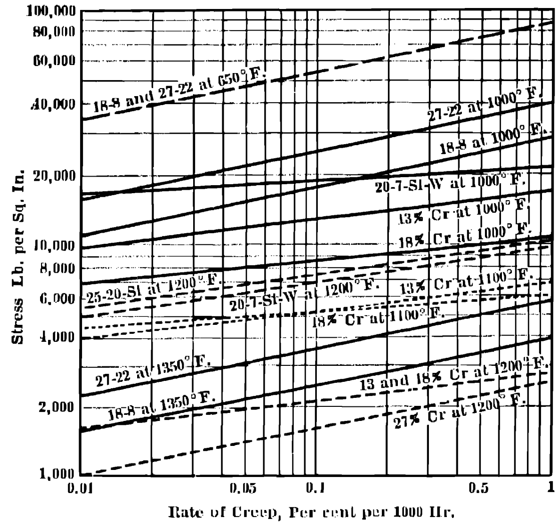

FIG. 1.—Creep Characteristics of High Alloy Steels as Determined at Massachusetts Institute of Technology. (From paper by E. E. Thum in *A.S.T.M. Symposium on High Strength Constructional Metals*, 1936.)

Approximate compositions are:

13 per cent Cr	0.11% C, 13% Cr	18–8	0.05% C, 17.6% Cr, 8.7% Ni
18 per cent Cr	0.10% C, 17.6% Cr	25–20–Si	0.12% C, 25.0% Cr, 20% Ni
27 per cent Cr	0.20% C, 27.0% Cr	27–22	0.60% C, 27.5% Cr, 22.5% Ni
20–7–Si–W	0.43% C, 20.0% Cr, 7.0% Ni, 1.4% Si, 0.6% W		

904. Copper Alloys of High Strength.—Properties of many of the older high-strength alloys of copper are given in Ch. XXVI. In addition, attention is here called to copper-silicon alloys and the heat-hardenable alloys of copper.

Copper-silicon alloys usually carry about 95 per cent copper, 2 or 3 per cent silicon, and smaller amounts of manganese. These alloys have the corrosion resistance of copper but much less electrical conductivity. In the annealed condition they possess the tenacity and ductility of soft steel. If hard drawn, strengths of 100,000 to 140,000 lb./in.^{2} are obtainable but with material sacrifice of ductility. The modulus of elasticity is about 15,000,000 lb./in.^{2} These alloys can be readily worked, either hot or cold, and are easily welded. Copper-silicon alloys find applications in building construction, air-conditioning equipment, and in hardware.

Of the heat-hardenable copper alloys, those of beryllium possess exceptional strengths and good resistance to atmospheric corrosion. The alloys containing 1.4 to 2.5 per cent beryllium, with or without small additions of nickel, can be materially strengthened and hardened by rolling and then heating for two hours or more at temperatures between 250 and 325° C. In the annealed condition these alloys are ductile and have tenacities of 50,000 to 70,000 lb./in.^{2} Heat treated, the tensile strengths of these alloys can be raised to 150,000 or 200,000 lb./in.^{2} The proportional limits approximate 50 per cent of the tensile strengths. The endurance limit is reported to be between 30,000 and 40,000 lb./in.^{2} This alloy has found applications in the landing gear of airplanes and in electrical devices. When price reduction can be affected, it should have a much enlarged field of use.

Alloys of copper containing 7 per cent of nickel and a like amount of tin and those containing 5 per cent of nickel, 5 per cent of aluminum, and about 1 per cent of silicon also respond to heat treatment and exhibit high strengths. The copper-nickel-aluminum-silicon alloy also possesses good toughness, hardness, and resistance to wear.

Copper-chromium alloys containing low percentages of chromium are heat hardenable at temperatures of 500 to 550° C. When so treated, C. H. Davis * reported that they have tenacities of 80,000 lb./in.^{2}, relatively high conductivities, and retain their properties at temperatures below the treating range.

905. Structural Aluminum Alloys.—Although the tensile strength of the strongest wrought aluminum alloy is only 70,000 lb./in.^{2}, these alloys deserve consideration herein because of their high strength-weight ratios. In contrast to the weight of steel of 490 lb./ft.^{3}, the structural alloys of aluminum weigh only 175 lb./ft.^{3}, or approximately a tenth of a pound per cubic inch. The modulus of elasticity is low and fairly constant at 10,300,000 lb./in.^{2} The coefficient of thermal expansion is high, about 0.000012 per °F. according to manufacturers' report, or nearly twice the coefficient of steel. The alloys possess good resistance to atmospheric corrosion but require protection when exposed to aggressive mine waters or industrial liquids.

Duralumin, the most important of the structural alloys, contains aluminum over 92 per cent, copper 3.5 to 4.5, magnesium 0.2 to 0.75, and manganese 0.4 to 1.0 per cent. In the manufacture of duralumin parts, plates, sheets, structural shapes, and bars are rolled; tubes are drawn; thick members forged; and a large number of miscellaneous shapes are extruded or pressed into shape. Aluminum alloys for sand castings, permanent mold castings, and die castings are also made with suitable additions of silicon or silicon and copper. Compositions and physical properties of some of the stronger aluminum alloys are given in Tables 1 and 2. These data are taken from the paper by E. H. Dix and J. J. Bowman in the *A.S.T.M. Symposium on High-Strength Constructional Metals*, 1936. Also see the *Structural Aluminum Handbook*, by the Aluminum Company of America.

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* A S.T.M. Symposium, 1936; also see M. G. Corson in *Iron Age*, October, 1938.

The hardness and strength of the aluminum alloys containing copper or magnesium silicide can be materially increased by heating parts at temperatures in the vicinity of 950° F., quenching, and aging. For the alloys 17S, Table 1, aging is done at room temperature, whereas alloys 14S and 27S are aged at approximately 300° F. Sometimes quenching causes distortion of preformed parts which is removed by suitable rolling or stretching. The significance of the temper letters and figures appended in alloy designations is indicated in the footnote of Table 2. If an alloy is susceptible of further treatment after quenching by heating at temperatures above normal, the condition following quenching is indicated by appending a " W " to the designation. Cold forming of such alloys can be done at the intermediate W-stage, and aging may then be done at proper temperature to improve the strength. Age hardening in 17S is retarded at temperatures of 20° F. and is nearly complete in 24 hours at 70° F., although a period of 4 days is usually allowed for completion of the aging effect on this alloy. Allowance for such behavior must be made in riveting this material.

Welding reduces the strength and hardness of duralumin parts in the vicinity of the weld. Sometimes this weakening effect can be offset by subsequent heat treatment.

As in steel, cold work, within limits, raises the strength of the wrought alloys but reduces the ductility and tends to reduce resistance to corrosion.

Protection of thin sheets severely exposed to corrosion is sometimes accomplished by coating with a thin layer of pure aluminum (as in the Alclad alloys), by producing through electro-chemical method an oxide coating, or by painting.

Of the alloys whose properties are shown in Tables 1 and 2, 17S–T has been the most widely used in sheet, plate, wire, rods, shapes, tubing, and forgings. It has been considerably used in truck and bus bodies and in railroad and street car construction. Large quantities of 17S–T, or the Alclad variety, have also been used in aircraft construction, but the stronger alloy 24S–T appears to be superseding alloy 17S–T in that field. Alloy 27S–T, with its high-yield strength and good resistance to corrosion, finds applications in rolled structural shapes for bridges, dragline buckets and truck bodies. Though not readily formed cold, alloy 27S–T can be hot worked at 400° F. for a short period without detrimental effects. Alloy 14–S, susceptible of age hardening at normal temperatures and of further improvement by aging at higher temperatures, is the strongest of

TABLE 1.—NOMINAL COMPOSITIONS OF HIGH-STRENGTH ALUMINUM ALLOYS. (DIX AND BOWMAN)

Alloy No.	How Made	Heat-treatable	Alloying Element in Per Cent				
			Copper	Silicon	Manganese	Magnesium	Chromium
52S	Wrought	No	...	...	....	2.50	0.25
14S	"	Yes	4.4	0.8	0.75	0.35	....
17S	"	"	4.0	...	0.5	0.5	....
24S	"	"	4.2	...	0.5	1.5	....
27S	"	"	4.5	0.8	0.8	....	....
195	Cast	"	4.0	...	....	....	....
220	"	"	...	...	....	10.0	....
356	"	"	...	7.0	....	0.3	....

TABLE 2.—TYPICAL MECHANICAL PROPERTIES OF ALUMINUM ALLOYS. (DIX AND BOWMAN)

Alloy and Temper *	How Made	Heat-treatable	Tensile Strength, lb./in.^{2}	Yield Strength,† lb./in.^{2}	Elongation in 2 in., Per cent ‡	Brinell Hardness No.	Shear Strength, lb./in.^{2}	Endurance Limit, lb./in.^{2} §
52S-O	Wrought	No	29,000	14,000	25	45	18,000	17,000
52S-½H	"	"	37,000	29,000	10	67	21,000	19,000
52S-H	"	"	41,000	36,000	7	85	24,000	20,500
14S-T	Forged	Yes	68,000	53,000	12	130	45,000	....
17S-O	Wrought	Yes	26,000	10,000	20	45	18,000	11,000
17S-T	"	"	58,000	35,000	20	100	35,000	15,000
24S-O	Wrought	Yes	26,000	10,000	20	42	18,000	....
24S-T	"	"	65,000	43,000	20	105	40,000	14,000
27S-T	Wrought	Yes	60,000	50,000	9	115	37,000	13,000
195-T4	Cast	Yes	31,000	16,000	8	65	28,000	6,000
195-T6	"	"	36,000	22,000	4	80	30,000	6,500
220-T4	Cast	Yes	44,000	25,000	13	75	33,500	7,000
356-T6	Cast	Yes	32,000	22,000	4	70	23,000	8,000

* O signifies fully annealed; ½H and H indicate degree of cold rolling; T signifies full heat-treated temper; T4 represents solution heat-treated or as quenched condition.

† Based on a permanent set of 0.2 per cent.

‡ Values for wrought material are for $\frac{1}{16}$-in. sheets; 0.505-in. diam. specimens used for other material.

§ Based on 500,000,000 cycles of reversed bending in an R. R. Moore machine.

the alloys and is used for heavy forgings. Alloy 52S, not heat treatable, is used in sheets, plates, and rods where good resistance to corrosion and strength are required. For severe exposures, as in marine atmospheres, the aluminum-magnesium alloys are more resistant to corrosion than the aluminum-silicon, or aluminum-copper alloys.

The strongest of the cast alloys of aluminum are 195 and 220. Alloy 195 has been used for machine bases, crane trucks, and crane trolleys. Although 220 is stronger than 195 and superior for heavy-duty applications, it requires more care in casting. Alloy 356 is said to combine the good casting qualities of the silicon-aluminum alloys with the strength qualities of the heat-treatable alloys and is recommended for castings which must be tight under pressure.

The two most potent handicaps to a more extensive use of these valuable alloys are their low stiffness and high cost. The stiffness handicap can be eliminated in many cases by proper design. Per pound, structural shapes of 17S–T cost 10 or 12 times as much as similar parts in steel.

906. Structural Magnesium Alloys.—Although less strong than the duralumin alloys, the alloys of magnesium with 12 per cent or less of aluminum have a better strength-weight ratio than the duralumins, owing to their extreme lightness. The magnesium alloys being relatively soft are the easiest of the commercial metals to machine. These alloys weigh about 112 lb./cu. ft., or two-thirds as much as the duralumins. Unfortunately the modulus of elasticity is low, only 6,500,000 lb./in.^{2}, and the alloys are not so ductile or tough as the duralumins. The coefficient of thermal expansion is 0.000016, or 2½ times that of steel. Magnesium-base alloys have good resistance to inland atmospheres but as a class are less resistant to saline waters or atmospheres than the duralumins. When properly protected they can be used along the sea-coast.

Data on compositions and mechanical properties of five of the more important magnesium-aluminum alloys appear in Table 3. The typical properties are from *Dowmetal,* the publication of The Dow Chemical Company,* which provides much additional information on these and on other alloys of this type. The compressive strength is roughly 50 per cent greater than the tensile strength.

The magnesium alloys can be cast or wrought into shape in much the same way as the duralumins. Castings are improved in tenacity and ductility by heat treating at temperatures in the vicinity of 700° F. and cooling in air. The yield strength is raised by aging castings after treatment at temperatures near 350° F. However, aging reduces the ductility obtained after heat treatment as indicated for alloy 4 in Table 3. Forgings may also be aged to improve the yield strength of the forged metal. Plates and sheets can be obtained in the as-rolled, annealed, or hard-rolled conditions. Properties of alloy 7, Table 3, illustrate the differences in the extreme conditions. Structural shapes, bars and tubing are extruded in forming.

Bars and tubing 6 in. or less in diameter, and angles, I-beams and channels up to 5 or 7-in. sizes can be obtained. Plates ½-in. or less in thickness may be had up to 48 in. in width and length, or in 12-in. widths up to 16 ft. in length. Sheets as thin as 0.016 in. are available in widths of 30 in. or less and in lengths up to 6 ft. Extruded shapes range in price from 50 to 80 cents a pound in one ton quantities.

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* See also A.S.T.M. Symposium of 1936 for similar data.

TABLE 3.—DATA ON HIGH-STRENGTH, MAGNESIUM-BASE ALLOYS

COMPOSITION

A.S.T.M. Alloy No.*	Dow Chemical Co. No.	How Made	Alloying Elements in Per Cent Nominal Composition					
			Aluminum	Manganese min	Zinc	Copper max.	Silicon max.	Other Impurities
4	H	Cast or Wrought	5.3-6.7	0.1	2.5-3.5	0.05	0.5	0.3
14	P	Wrought	9.0-11.0	0.1	0.5-1.5	0.05	0.5	0.3
7	E	"	5.8-7.2	0.15	0.3 max.	0.05	0.5	0.3
8	J	"	5.8-7.2	0.15	0.2-0.8	0.05	0.5	0.3
15	X	"	2.5-3.5	0.20	2.5-3.5	0.05	0.5	0.3

TYPICAL MECHANICAL PROPERTIES † FROM *Dowmetal.*

No.	How Made	Condition of Alloy	Tensile Strength, lb. in.^{2}	Yield Strength, lb., in.^{2}	Elongation in 2 in., Per Cent	Brinell Hardness No.	Shear Strength, lb./in.^{2}	Endurance Limit, lb./in.^{2}
H	Cast	As cast	27,000	12,000	5	50	16,000	10,000
		Heat-treated	38,000	12,000	11	51	16,000	10,000
		Ht-tr. and aged	38,000	18,000	5	62	18,000	10,000
P	Cast	Ht-tr. and aged	36,000	22,000	1	77	20,000	......
H	Forged	Press-forged	45,000	30,000	9	65	.....	18,500
	Forged	P. F. and aged	46,000	34,000	5	83	.....	18,500
E	Rolled	Hard rolled	45,000	34,000	9	70	.....	......
		Annealed	39,000	20,000	15	57	.....	......
J	Extruded	As extruded	43,000	30,000	17	54	20,000	17,000
X	Extruded	As extruded	42,000	30,000	19	51	20,000	18,000
		Extr. and aged	44,000	34,000	13	54	21,000	17,000

* See *A.S.T.M.*, Des. B80-38T, B91-38T, B107-38T, for minimum strength and ductility requirements for these and other alloys.

† Properties determined as indicated in footnote for Table 2.

The magnesium alloys are welded with difficulty. Hence riveting is the preferred method of uniting parts. For such purposes aluminum rivets can be used if driven according to directions.

Of the alloys shown in the Table 3, alloys 4 and 15 are the most resistant to salt-water attack. A manufacturer claims that an alloy of magnesium with about 1.5 per cent of manganese, no aluminum, and less than 0.3 per cent of silicon makes a plate metal more resistant to salt water than any of the alloys listed in the table.

The principal field of use for the magnesium-base alloys has been in aircraft construction, for wheels, housings, brackets, crankcases, and engine parts not subject to attrition. Sheets and extruded shapes have found use in the construction of trucks and buses.

APPENDIX A

STANDARD METHODS
OF
MAKING COMPRESSION TESTS OF CONCRETE[1]

A.S.T.M. Designation: C 39–33

These methods are issued under the fixed designation C 39; the final number indicates the year of original adoption as standard or, in the case of revision, the year of last revision.

ISSUED AS TENTATIVE, 1921; ADOPTED, 1925; REVISED, 1927, 1933.

1. *Scope.*—These methods are intended to cover compression tests of concrete made in a laboratory where accurate control of quantities of materials and test conditions is possible. They are designed to apply primarily to hand-mixed concrete compression specimens, but may be used with slight modification in making tests of concrete for wearing resistance, bond between concrete and steel, impermeability, etc. The investigation of machine-mixed concrete will require certain obvious changes in the methods. For the method of making and storing compression test specimens of concrete made during the progress of construction work, see the Standard Method of Making and Storing Compression Test Specimens of Concrete in the Field (A.S.T.M.Designation: C 31) of the American Society for Testing Materials.[2]

2. *Sampling for Preliminary Tests.*—Representative samples of all concrete materials shall be secured for preliminary tests prior to the proportioning and mixing of the concrete. Test samples of cement may be made up of a small quantity from each sack used in the concrete tests. Test samples of aggregates may be taken from larger lots by quartering.

3. *Preparation of Materials.*—Materials shall be brought to room temperature (18 to 24° C., 65 to 75° F.) before beginning the tests. Cement shall be stored in a dry place; preferably in covered metal cans. The cement shall be thoroughly mixed in advance, in order that the sample may be uniform throughout the tests. It shall be sieved through a No. 16 (1190-micron) sieve and all lumps rejected. Aggregates shall be in a room-dry condition when used in concrete tests.* In general, aggregates should be separated on the No. 4 (4760-micron), $\frac{3}{8}$-in. and $1\frac{1}{2}$-in. sieves and recombined to the average original sieve analysis for each batch. Fine aggregate should be separated into different sizes also, in cases where unusual gradings are being studied.

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[1] Under the standardization procedure of the Society, these methods are under the jurisdiction of the A.S.T.M. Committee C-9 on Concrete and Concrete Aggregates.

[2] 1938 Supplement to Book of A.S.T.M. Standards.

* *Author's Note:* Some prefer to use aggregates in saturated surface-dry condition.

4. *Cement Tests.*—Cement shall be tested in accordance with Standard Methods of Sampling and Testing Portland Cement (A.S.T.M. Designation: C 77) of the American Society for Testing Materials.[1]

5. *Fine Aggregate Tests.*—Fine aggregates (passing through a No. 4 (4760-micron) sieve) shall be subjected, when required, to the following tests * of the American Society for Testing Materials:

(*a*) Sieve analysis test made in accordance with the Tentative Method of Test for Sieve Analysis of Fine and Coarse Aggregates (A.S.T.M. Designation: C 136).[2]

(*b*) Test for organic impurities made in accordance with the Standard Method of Test for Organic Impurities in Sands for Concrete (A.S.T.M. Designation: C 40)[3]

(*c*) Test for quantity of silt, clay, and dust made in accordance with the Standard Method of Test for Amount of Material Finer than No. 200 Sieve in Aggregates (A.S.T.M. Designation: C 117)[4]

(*d*) Test for unit weight made in accordance with the Standard Method of Test for Unit Weight of Aggregate for Concrete (A.S.T.M. Designation: C 29).[5]

(*e*) Strength test of 1 : 3 mortar by weight at 7 and 28 days in comparison with standard sand mortar in accordance with Standard Methods of Sampling and Testing Portland Cement (A.S.T.M. Designation: C 77).[1]

6. *Coarse Aggregate Tests.*—Coarse aggregates (retained on a No. 4 (4760-micron) sieve) shall be subjected when required to the following tests: *

(*a*) Sieve analysis test as specified in Section 5 (*a*);

(*b*) Test for quantity of silt, clay, and dust made in accordance with the Standard Method of Test for Amount of Material Finer than No. 200 Sieve in Aggregates (A.S.T.M. Designation: C 117) of the American Society for Testing Materials.[4]

(*c*) Test for unit weight as specified in Section 5 (*d*).

7. *Unit Weight of Mixed Aggregate.*—The unit weight of mixed fine and coarse aggregates as used in concrete tests shall be determined in accordance with the method specified in Section 5 (*d*).

8. *Proportioning.*—The quantities of each size of aggregate to be used in each batch shall be determined on the basis of the sieve analysis and the unit weight of the mixed aggregates. The exact quantities of cement and of each size of aggregate for each batch shall be determined by weight. The quantity of water for each batch shall be accurately measured. The quantities of materials may be expressed as (*a*) 1 volume of cement to .... volumes of total aggregate mixed as used, or (*b*) 1 volume of cement, ... volumes of fine aggregate, and .... volumes of coarse aggregate, or (*c*) 1 part by weight of cement .... parts by weight of fine aggregate, and .... parts by weight of coarse aggregate.

NOTE.—It is impracticable to give a general method for proportioning concrete for experimental purposes; the details will necessarily vary widely with the purpose for which the tests are made. The following procedure is suggested for specific cases:

(*a*) Vary the cement content by 10-per-cent intervals above and below assumed quantity.

(*b*) Vary the proportions of fine to coarse aggregate, measured separately, at intervals of 10 per cent.

(*c*) Vary the quantity of mixing water by intervals of 10 per cent.

9. *Size and Shape of Specimens.*—Compression tests of concrete shall be made on cylinders of diameter equal to one-half the length. The standard shall be 6 by 12-in. cylinders where the coarse aggregate does not exceed 2-in. in size; for aggregates larger

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[1] 1937 Supplement to Book of A.S.T.M. Standards, p. 54.

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 38, Part I (1938); also 1938 Book of A.S.T.M. Tentative Standards.

[3] 1936 Book of A.S.T.M. Standards, Part II, p. 350.

[4] 1937 Supplement to Book of A.S.T.M. Standards, p. 99.

[5] 1936 Book of A.S.T.M. Standards, Part II, p. 364.

* *Author's Note:* For specific gravity test methods for aggregates see Des. 128–36T and 127–36T.

than 2 in., 8 by 16-in. cylinders shall be used; 2 by 4-in. cylinders may be used for mixtures without coarse aggregate.

10. *Mixing Concrete.*—Concrete shall be mixed by hand in batches of such size as to leave a small quantity of concrete after molding a single test specimen.* The batch shall preferably be mixed in a shallow metal pan with a 10-in. bricklayer's trowel which has been blunted by cutting off about $2\frac{1}{2}$ in. of the point, as follows:

(*a*) The cement and fine aggregate shall be mixed dry until the mixture is homogeneous in color;

(*b*) The coarse aggregate shall be added and mixed dry;

(*c*) Sufficient water shall be added to produce concrete of the required workability;

NOTE.—Concrete tests should be made on plastic mixtures. It is of the utmost importance that a uniform degree of workability be secured in tests involving comparisons of different materials and methods.

(*d*) The mass shall be mixed thoroughly until the resulting concrete is homogeneous in appearance.

11. *Workability.*—The workability or plasticity of each batch of concrete shall be measured immediately after mixing by one of the following methods:

(*a*) Slump test made in accordance with the Tentative Method of Test for Consistency of Portland-Cement Concrete (A.S.T.M. Designation: D 138–32 T) of the American Society for Testing Materials.[1]

(*b*) Flow test made by placing a metal mold in the shape of a frustum of a cone $6\frac{3}{4}$ in. in top diameter, 10 in. in bottom diameter, 5 in. in depth, on the table of the flow apparatus.[2] The fresh concrete shall be placed in the mold in two layers. Each layer shall be rodded as described in Section 13. Immediately after molding, the surplus concrete shall be struck off with a trowel and the mold shall be removed by a steady upward pull; the table raised $\frac{1}{2}$ in. and dropped 15 times in about 10 seconds by means of a suitable cam and crank. The spread of the fresh concrete due to this treatment expressed as a percentage of the original bottom diameter of the cone is the "flow."

12. *Molds.*—The molds shall preferably be of metal. Each mold shall be provided with a machined metal base plate, and shall be oiled with a heavy mineral oil before using. Particular care shall be taken to obtain tight molds so that the mixing water will not escape during molding.

NOTE.—The best type of mold consists of lengths of cold-drawn steel tubing, split along one element and closed by means of a circumferential band and bolt. Satisfactory molds can be made from lengths of steel water-pipe machined on the inside, from rolled metal plates, from galvanized steel, machined iron or steel castings. Paraffined cardboard molds will give good results under expert supervision.

13. *Molding Test Specimens.*—The test specimens shall be molded by placing the fresh concrete in the mold in three layers, each approximately one third the volume of the mold. In placing each scoopful of concrete, the scoop shall be moved around the top edge of the mold as the concrete slides from it in order to insure a symmetrical distribution of concrete within the mold. Each layer shall be rodded with 25 strokes of a $\frac{5}{8}$-in. rod 24 in. in length, bullet-pointed at the lower end. The strokes shall be distributed in a uniform manner over the cross-section of the mold and shall penetrate into the underlying layer. The bottom layer shall be rodded throughout its depth. After the top layer has been rodded the surface of the concrete shall be struck off with a trowel

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* *Author's Note:* For a series of identical specimens to be tested at different ages the batch may be made large enough for 3, 5, or 7 specimens if the mixing procedure is maintained uniform.

[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 32, Part I, p. 775 (1932); also 1938 Book of A.S.T.M. Tentative Standards.

[2] For a description and illustration of one design for a flow-table, see *Proceedings*, Am. Soc. Testing Mats., Vol. XX, Part II, p. 242 (1920); also *Concrete*, p. 274, June, 1920.

and covered with a glass plate at least ¼ in. in thickness or with a machined metal plate, which may later be used in capping the test specimens.

14. *Capping Specimens.*—Two to four hours after molding, the test specimens shall be capped with a thin layer of stiff neat-cement paste in order that the cylinder may present a smooth end for testing. The cap shall be formed by means of a piece of plate glass ¼ in. in thickness or a machined metal plate ½ in. in thickness and of a diameter 2 or 3 in. larger than that of the mold. The plate shall be worked on the cement paste until the plate rests on top of the mold. The cement for capping should be mixed to a stiff paste 2 to 4 hours before it is to be used in order to avoid the tendency of the cap to shrink. Adhesion of the concrete to the top and bottom plates may be avoided by oiling the plates or by inserting a sheet of paraffined paper.

15. *Curing Test Specimens.*—Concrete test specimens shall be removed from the molds 20 to 48 hours after molding, marked, weighed and stored in damp sand, under damp cloths or in a moist chamber until the date of test. The temperature of the curing room should not fall outside the range of 18 to 24 C. (65 to 75 F.)

16. *Age at Test.*—Tests shall be made at the age of 7 and 28 days; ages of 3 months and 1 year are recommended, if longer-time tests are required.

17. *Sequence of Tests.*—Three to five test specimens should be made on different days in investigations in which accurate comparisons are desired.

18. *Preparation of Tests.*—Compression tests shall be made immediately upon removal of the concrete test specimens from the curing room; that is, the test specimens shall be loaded in a damp condition. The length and average diameter of the test specimen shall be measured in inches and hundredths; two diameters shall be measured at right angles near the mid-length. The test specimen shall be weighed immediately before testing.

19. *Method of Testing.*—In general, only the ultimate compressive strength of the cylinders need be observed. The metal bearing plates of the testing machine shall be placed in contact with the ends of the test specimen; cushioning materials shall not be used. An adjustable bearing block shall be used to transmit the load to the test specimen. The bearing block shall be used on *top* of the specimen in vertical testing machines. The diameter of the bearing block shall be the same or slightly larger than that of the test specimen. The upper or lower section of the bearing block shall be kept in motion as the head of the testing machine is brought to a bearing on the test specimen.

20. *Application of Load.*—The load shall be applied uniformly and without shock. The moving head of the testing machine should travel at the rate of about 0.05 in. per minute when the machine is running idle.*

21. *Record of Tests.*—The total load indicated by the testing machine at failure of the test specimen shall be recorded and the unit compressive strength calculated in pounds per square inch, the area computed from the average diameter of the cylinder being used. The type of failure and appearance of the concrete shall be noted.

22. *Weight of Concrete.*—The weight of the concrete in pounds per cubic foot shall be determined from the weight of the specimens and their dimensions.

23. *Density and Yield.*—Density and yield of concrete when required shall be calculated from the unit volumes of the constituent materials and the volume of the fresh or set concrete as desired. Density is here understood to be the ratio of solids in the concrete to the total volume of the mass. Yield is the volume of concrete resulting from the volume of aggregate mixed as used.

Report.—The report shall include the following:

(*a*) The kind and origin of concrete materials;

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* *Author's Note:* To expedite testing, a load of ½ the estimated ultimate may be applied at a rapid controlled rate, then reduced to 0.05 in./min., or for hydraulic machines to 250 lb./in.^{2}/min., for final loading.

(*b*) Complete data on all tests of cement and aggregates;

(*c*) A description of methods of making and testing the concrete, where methods deviate from the proposed standards;

(*d*) The quantities of cement, aggregates and water in each batch;

(*e*) The method of measuring workability or plasticity with "slump" or "flow" of concrete;

(*f*) The quantity of water expressed as a ratio to volume of cement;

(*g*) The age at test;

(*h*) The size of test specimens;

(*i*) The date of molding and testing each cylinder;

(*j*) The compressive strength in pounds per square inch of each test specimen and the average of tests in a set;

(*k*) A description of failure and appearance of concrete on each test specimen;

(*l*) The unit weight, density and yield of the concrete.

APPENDIX B

SOCIETY OF AUTOMOTIVE ENGINEERS NUMBERING SYSTEM FOR STEELS

This Society has adopted a standard numeral index system by which it is possible to designate with four or five figures any steel desired. The first figure indicates the class to which the steel belongs. The eight classes and their numerals are

Carbon steels	1	Chromium steels	5
Nickel steels	2	Chrome-vanadium steels	6
Chrome-nickel steels	3	Tungsten steels	7
Molybdenum steels	4	Silicon-manganes steels	8

For the alloy steels the second figure shows the percentage of the most important alloying element. The last two or three figures generally designate the carbon content, usually within ±0.05 per cent. For example, 1015 indicates a carbon steel with 0.10

BASIC NUMERALS AND DIGIT RANGES FOR S.A.E. STEELS

(For chemical compositions of each of the 110 grades of steel see S.A.E. Handbook)

Type of Steel	Numeral	Digit Range *	No. of Grades
Carbon Steels	1		
Plain Carbon (C 0.05–1.05%)		1010–1095	26
Free Cutting, (Screw Stock, S <0.3%)		1112–1120	4
Free Cutting, (Manganese, Mn 1.0–1.65%)		X1314–X1340	5
High Manganese (Mn 1.6–1.9%)		T1330–T1350	5
Nickel Steels	2		
0.50 Per Cent Nickel		2015	1
1.50 Per Cent Nickel		2115	1
3.50 Per Cent Nickel		2315–2350	7
5.00 Per Cent Nickel		2515	1
Nickel Chromium Steels	3		
1.25 Per Cent Nickel, 0.60 Per Cent Chromium		3115–3150	9
1.75 Per Cent Nickel, 1.00 Per Cent Chromium		3215–3250	6
3.50 Per Cent Nickel, 1.50 Per Cent Chromium		3312–3340	4
3.00 Per Cent Nickel, 0.80 Per Cent Chromium		3415–3450	3
Corrosion and Heat Resisting (Cr 17–20, Ni 8–10%)		30905–30915	2
Molybdenum Steels (Mo <0.40%)	4		
Chromium (Cr <1.10%)		4130–4150	5
Chromium Nickel (Cr <0.90, Ni <2.0%)		4320–X4340	3
Nickel (Low) (Ni <2.00%)		4615–4640	3
Nickel (Medium) (Ni <3.75%)		4815–4820	2
Chromium Steels (Cr <1.50%)	5		
Low Chromium (Cr 0.6–1.10%)		5120–5150	3
Medium Chromium (Cr 1.20–1.50%)		52100	1
Corrosion and Heat Resisting (Cr 11.5–18.0%)		51210–51710	5
Chromium Vanadium Steels (Cr <1.10, Va <0.25%)	6	6115–6195	9
Tungsten Steels (Cr <4.00, W <15.0%)	7	71360–7260	3
Silicon Manganese Steels (Mn 0.6–0.9, Si 1.8–2.2%)	9	9255–9260	2

* X is prefixed to denote variations in range of elements. T is prefixed to manganese steels to avoid confusion with certain other steels of same numeral but different manganese content.

to 0.20 per cent carbon; 2335 indicates a nickel steel with 3.25 to 3.75 nickel and 0.30 to 0.40 per cent carbon; 3140 signifies a chrome-nickel steel with 0.45 to 0.75 chromium, 1.0 to 1.5 nickel, and 0.35 to 0.45 per cent carbon; 52100 designates a chromium steel with 1.2 to 1.5 chromium and 0.95 to 1.10 per cent carbon.

Since these numbers are much used in the designation and purchase of steels for industrial purposes, the table on the previous page has been inserted to show the range of compositions included in the system. The society also has standard heat treatments for many of these steels. Both heat treatments and charts may be found in the S.A.E. Hand book, an annual publication.

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